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ABSTRACT

This student manual contains the following six units for classroom and laboratory experiences in high school industrial electronics: (1) introduction and review of DC and AC circuits; (2) semiconductors; (3) integrated circuits; (4) digital basics; (5) complex digital circuits; and (6) computer circuits. The units include unit objectives, specific objectives, informational material, and exercises. Materials are illustrated with line drawings. (KC)

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INDUSTRIAL ELECTRONICS II
for ICT

Student's Manual

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Preface

This material has been written to serve the needs of high school students who wish to continue their education in the field of electronics. The material was developed specifically for students who wish to learn industrial electronics. However, at this level, the course is broad enough to allow a student to enter any area of electronics.

In order to succeed in this field, students should have a good foundation in mathematics, chemistry, and physics. Good communication skills will also improve their chances of success.

Students will need a knowledge of algebra to understand and apply the material presented throughout this publication. An understanding of physics and chemistry will help the students understand the internal structure of the components described in the text.

Acknowledgments

Sincere thanks and appreciation are extended to the following members of our advisory committee for their assistance in this project:

- Mr. Chris Brock, The University of Texas at Austin, Applied Research Lab, Balcones Research Center
- Mr. Larry Milam
- Mr. Doug Holberg, Consulting Engineer, has earned a special note of appreciation. His knowledge, dedication, and sense of humor improved the quality of the text, kept the project on schedule, and made the development of this curriculum enjoyable.

Unit

A

Introduction and Review

A-1: Review of DC and AC Circuits

8

A-1

Review of DC and AC Circuits

UNIT OBJECTIVE: Upon completion of this instructional unit, the student will be able to demonstrate a residual knowledge of Industrial Electronics I studied last year.

SPECIFIC OBJECTIVES: Upon completion of this assignment, the student(s) will be able to demonstrate a knowledge of:

- dc and ac electronic theory studied last year
- reactance, impedance, and resonance studied last year

OHM'S LAW

The most basic mathematical relationship in electronics is the relationship between voltage, current, and resistance. ***Your background in algebra classes will help you understand how Ohm's law defines that relationship***. The basic formula for Ohm's law is:

$V = IR$ *formula 1*

This formula states that the voltage (V) is equal to the current (I) multiplied by the resistance (R). We can use algebraic methods to move the terms of this formula around and solve for the current I.

$I = \frac{V}{R}$ *formula 2*

Formula 2 states that the current is equal to the voltage divided by the resistance. We can use algebra again to find a formula that will give us the resistance.

$R = \frac{V}{I}$ *formula 3*

Formula 3 tells us that the resistance is equal to the voltage divided by the current. Figure 1 is designed to help you memorize the Ohm's law formulas.

Use your calculator to determine the amount of voltage across a 1 kΩ resistor with 3 mA of current flowing through it. Remember that the *k* is 10^3 or three zeros following the 1 and that mA is 10^{-3} or three places past the decimal point. If your answer to this problem is 3 V, you are correct.

You should also remember the power formulas. The power dissipated in a circuit is equal to the voltage across the circuit times the current that flows through the circuit.

$$P = VI \qquad \textit{formula 4}$$

How much power is dissipated in the 1 kΩ resistor with the 3 V across it? According to formula 4, the 3 V times the 3 mA will give 0.009 watt or 9 mW of power. So, 9 mW of power is dissipated in the resistor.

Resistors that are connected in series can simply be added to find the total resistance. If the resistors are in parallel, we can find the conductance for each resistor first. The conductance is equal to the inverse of the resistance. Just enter the resistance into your calculator and press the 1/X button, and the conductance should be displayed. Add the conductance of each of the parallel resistors, and then enter this number into your calculator and press the 1/X button again to get the resistance. This will be the total combined parallel resistance of the circuit. We can show this in formula form in formula 5.

$$R_T = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots \frac{1}{R_n}} \qquad \textit{formula 5}$$

THEVENIN AND NORTON EQUIVALENT CIRCUITS

Thevenin and Norton found a method of developing a circuit that would have the same output as the original circuit and contain only two components. Both the Thevenin and Norton equivalent circuits use an ideal source and an ideal resistance. These two components result in a much simpler circuit than the original circuit. The Thevenin circuit will use a voltage source for its ideal source, and the Norton circuit will use a current source.

The concept of an ideal voltage source or ideal current source is important. The ideal or perfect voltage or current source does not exist as a real circuit. It can only exist as a theoretical concept. An ideal voltage source would have no resistance in series with it. All real voltage sources have some resistance in series with the flow of current. An ideal voltage source, with a 10 V output, will have exactly 10 V on its output whether the output is shorted or open.

A real voltage source that approaches or comes close to being an ideal voltage source will have a small amount of series resistance. If the ratio of the load resistance to the series resistance is greater than 100 to 1, the variation in output voltage with changes in the load will be small. This kind of circuit would approximate an ideal voltage source. For a current source, the resistance is in parallel with the ideal source. This combination of ideal current source and resistance in parallel approximates a real current source. The larger the resistance is—that is, in parallel with the source—the more the circuit will behave like an ideal current source.

We can find the Thevenin or Norton equivalent circuit for any complex circuit, for the portion of its output that is linear. When the output is linear, the output will change at the same rate as changes in the input. The first step in finding the Thevenin or Norton equivalent circuit is to disconnect the load. For the Thevenin equivalent circuit, the second step is to determine the voltage on the two terminals that are now open as a result of removing the load. If you were looking for the Norton equivalent circuit first, then you would need to find the current that would flow if the output terminals were shorted. The voltage across the terminals or the short circuit current is the value of the voltage or current source in the equivalent circuit. The third step, which is valid for both Thevenin and Norton, is to find the Thevenin or Norton equivalent resistance. This can be done by replacing the voltage sources with shorts and the current sources with opens. Looking into the two terminals is the same as finding the resistance across the two terminals. This can be done with a meter or mathematically. This resistance value is the resistance for the Thevenin or Norton equivalent circuits.

The Thevenin equivalent resistance is the same as the Norton equivalent resistance. You can find the Norton equivalent current source by using Ohm's law. Simply divide the Thevenin equivalent voltage source by the Thevenin equivalent resistance, and the resulting current is the Norton equivalent current source. Both the Thevenin and Norton circuits are related to each other according to Ohm's law.

KIRCHHOFF'S LAW

Kirchhoff's voltage law simply states that the sum of the voltage drops around any loop is equal to zero. This is a law that you will frequently use when analyzing circuits and troubleshooting.

If we let the voltage source V_S, in figure 2, equal 10 V, what is the voltage drop across R_1? Kirchhoff's voltage law states that the sum of the voltage drops must equal zero; therefore, the voltage drop across R_1 must be also equal to 10 V to cancel out the 10 V from the source. We have a complete loop with the voltage source and the resistance R_1 in figure 2. Another loop is the resistance R_1, R_2, and R_3. This will result in 10 V across R_2 and R_3 to balance the 10 V across R_1.

Kirchhoff's current law states that the sum of the current entering a node or some point must equal the sum of the current leaving that node or point. To many people, this is obvious. What goes in must come out. Although the concept is obvious, Kirchhoff's current law is the basis for many important mathematical concepts.

CURRENT FLOW: CONVENTIONAL OR ELECTRON?

When current is flowing in a wire or any other device, the only things flowing or moving are the negative electrons. The electrons travel into the positive terminal and leave out the negative terminal of a device. If we allow ourselves to be technically correct when we work problems in electronics, we will be using negative numbers for the normal flow of current. In order to avoid the added difficulty of being forced to use negative numbers for most computations in electronics, engineers use conventional current flow instead of electron flow. Conventional current flow shows the normal current flow as positive instead of negative. Unless we are discussing electron flow at the atomic level, we will also use conventional current flow in our discussions.

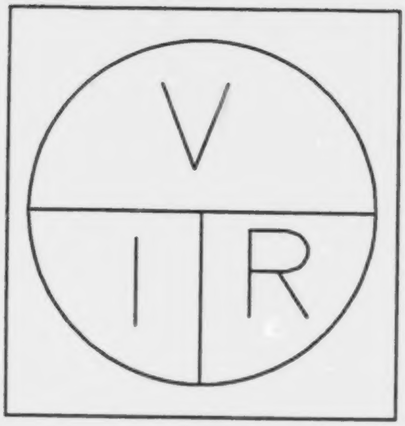

Figure 1

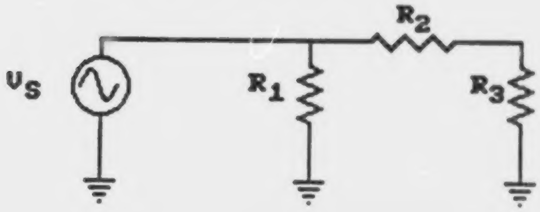

Fig. 2. Charging a capacitor

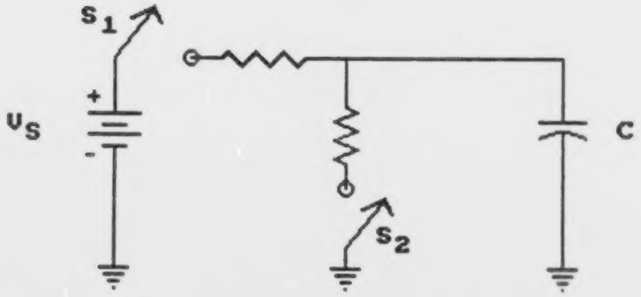

Figure 3

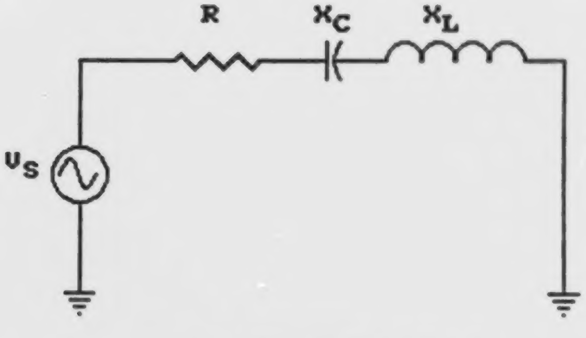

Fig. 4. Series RCL circuit

CAPACITORS AND INDUCTORS

In your previous studies, you probably noticed that, in electronics, capacitors appear to be the opposite of inductors. The capacitor is constructed of two plates with an insulator separating them. The amount of capacitance depends on the size of the plates, the distance between the plates, and the material that is used for the insulator between the plates. This insulator is called the dielectric. Bringing the plates closer together or increasing the size of the plates will increase the capacitance. For an inductor, we can increase the number of windings or add an iron core to increase the amount of inductance.

When combining capacitors in parallel, we treat them like resistors in series. Capacitors in series are treated like resistors in parallel. Inductors in series and in parallel are treated the same as resistors.

TIME CONSTANTS

The reactance of a capacitor or inductor can be used for timing purposes. Timing circuits using capacitors are more common than inductors. A capacitive resistive timing circuit is often called an *RC circuit*.

The circuit in figure 3 will show how a capacitor and a resistor can be used to create a timing circuit. We can start with the capacitor discharged and switch S_2 open. Closing switch S_1 will then cause the current to flow through the resistor in series with S_1, and charge the capacitor. The unit of time in which the capacitor is charged is called the *RC time constant*. Five time constants will result in a fully charged capacitor. One time constant, in seconds, is equal to the capacitance times the resistance. Opening switch S_1 and closing S_2 will discharge the capacitor at the rate determined by the RC time constant or the capacitance times the resistance in series with S_2.

SERIES AND PARALLEL RCL CIRCUITS

The capacitive reactance and inductive reactance will both cause a 90° phase shift between the applied voltage and the current. Remember that a complete cycle of a sine wave is 360°. If we compared two sine waves on an oscilloscope that were 90° out of phase with each other, one sine wave would be crossing the zero line when the other sine wave was at its peak. In a capacitive circuit, the current leads the applied voltage by 90°, while in an inductive circuit the voltage leads the current by 90°. If we have a circuit with both capacitance and inductance, the phase shift will be the sum of the two 90° shifts or 180°. At 180° they are exactly opposite each other and will cancel each other. In a circuit with capacitance, inductance, and resistance in series, the capacitance and inductance will cancel each other. The remaining reactance will then cause a 90° phase shift with the resistance in the circuit. Once we have a circuit with just the capacitive or inductive reactance, we can use the Pythagorean theorem to find the impedance. The impedance, usually labeled "Z," is the combined total of resistance and reactance of a circuit. Formula 6 is the Pythagorean theorem and states that the impedance is equal to the square root of the sum of the squares of the resistance and reactance in the circuit. We will use the resistance and reactance in a series circuit and the resistive and reactive current in a parallel circuit.

$Z = \sqrt{R^2 + X^2}$ or $I_T = \sqrt{I_R{}^2 + I_X{}^2}$ *formula 6*

We can find the phase shift angle, which we usually label θ, from formula 7. The angle θ is equal to the arctan of the reactance over the resistance.

$\theta = \arctan \frac{X}{R}$ *formula 7*

In figure 3, we can let V_S be equal to 10 V, resistance R be equal to 1.2 kΩ, X_C be equal to 2.4 kΩ, and X_L be equal to 1.8 kΩ. Find the impedance Z of this series circuit using your calculator and some scrap paper. You will notice that this circuit is capacitive since there is more X_C than X_L. The 2.4 kΩ minus the 1.8 kΩ gives a difference of 600 Ω. We can now look at the circuit as if there were only the resistance and capacitive reactance in the circuit. To find the impedance, use formula 6 and your calculator. Take the 600 first, square it, and put the result in memory. Next, square the 1,200 (watch the decimal point), and add it to the 600 squared. You should now have 1.8 million in your calculator. Take the square root of this 1.8 million for the impedance of 1.34 kΩ. Round your numbers off to the three most significant numbers. There is little value in giving an answer of 1341.6408 Ω when the numbers that you used to calculate this result are not that accurate.

Now we can go a step further by dividing the 10 V from the source by the impedance just found to obtain 7.46 mA of current. What is the phase difference between the voltage and current in this circuit? Use formula 7 and your calculator to find the angle θ. You should not need any scrap paper for this computation. The 600 divided by the 1,200 will give you 0.5. Find the arctan of 0.5 for an answer of 26.6°. This circuit is capacitive, which will result in a negative angle.

Remember that the current in a series circuit is the same throughout the circuit and that the voltage across the components of a parallel circuit is the same across each component. The variable in the series circuit that we just finished was the voltage. In figure 5 the current will be the variable since this is a parallel circuit. We can use the same values for figure 5 as we did for figure 4. Use your calculator and some scrap paper to find the impedance of the parallel circuit in figure 5. Start by dividing the 10 V, which is across each component, by the reactance or resistance of that component to find the individual currents. The 10 V divided by the 1.2 kΩ resistance will equal 8.3 mA. The current through the capacitor is 4.2 mA, and the current through the inductor is 5.6 mA. The current through the inductor is 180° out of phase with the current through the capacitor. This 180° phase shift will allow us to take the difference between the inductive current and capacitive current. Notice that there is more inductive current than capacitive current in this circuit although we used the same values for the components. Next we can find the total current by using the Pythagorean theorem, or formula 6. Watch your decimal point, and find the square root of the sum of the squares of the 1.4 mA inductive current and 8.3 mA resistive current. The reactive current is small compared to the resistive part of the current, which results in a figure close to the inductive current for the total. The total current is 8.4 mA. Dividing this 8.4 mA by the 10 V will give us close to 1.2 kΩ of circuit impedance. Now we can find the phase angle θ by dividing the reactive current by the resistive current and taking the arctan of it. The arctangent of 1.4 mA divided by 8.3 mA is 9.6°.

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RESONANCE

If we go back to figure 4 and change the values of X_C and X_L so that they are equal to each other, the circuit will be resonant. The inductive reactance and capacitive reactance will completely cancel each other and leave just the resistance. The 1.2 kΩ resistance is too large for the formulas that we use to examine resonant circuits. The Q of the circuit should be greater than 10 to use most of the resonant circuit formulas. Formula 8 shows that the Q of a resonant circuit is the ratio of the inductive reactance to the resistance of the circuit.

$$Q = \frac{X_L}{R} \qquad \textit{formula 8}$$

The 1.8 divided by 1.2 would result in a very low Q. Let's change the resistance to 12 Ω, which will give a Q of 150. Remember that the Q of a circuit can be thought of as the *quality* of the circuit. If the resonant circuit is used for a bandpass filter, a higher Q will result in a sharper cutoff and a smaller bandpass. You can find the frequency at which the circuit is resonant by using formula 9. Remember that, as the frequency changes, the circuit will change from an inductive or capacitive circuit to resonance and then to a capacitive or inductive circuit. At resonance, a series circuit will have minimum impedance, and a parallel or tank circuit will have maximum impedance. Use formula 9 to find the resonant frequency of the circuits in figures 4 and 5. Use a capacitance of 0.002 μF and an inductance of 80 μH.

$$f_r = \frac{1}{2\pi\sqrt{LC}} \qquad \textit{formula 9}$$

Try doing the complete computation on your calculator without using any scrap paper. The resonant frequency comes close to 400 kHz. The three most significant numbers would be 398 kHz. Now that we have the resonant frequency, we can use formulas 10 and 11 to find the reactance of the capacitor and inductor.

$$X_C = \frac{1}{2\pi fC} \qquad \textit{formula 10}$$

$$X_L = 2\pi fL \qquad \textit{formula 11}$$

Use your calculator to find the reactance and try to work the complete problem in your calculator. You should obtain a number very close to 200 Ω for both the inductive and capacitive reactance.

EXERCISE: Read each question carefully, and take your time. Use your notebook paper or scrap paper to solve the problem. Round off your answer to the three most significant digits.

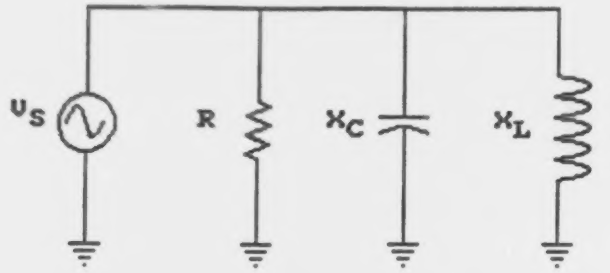

Fig. 5. Parallel RCL circuit

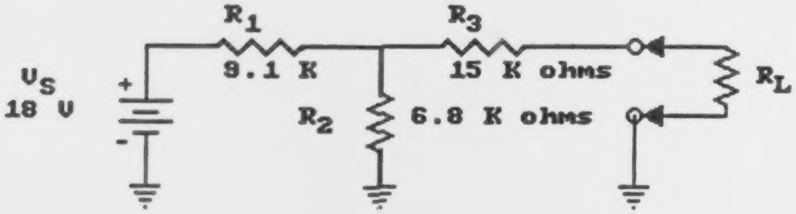
R_1
9.1 K
R_3
15 K ohms
R_L
V_S
18 V
+
-
R_2
6.8 K ohms

Figure 6

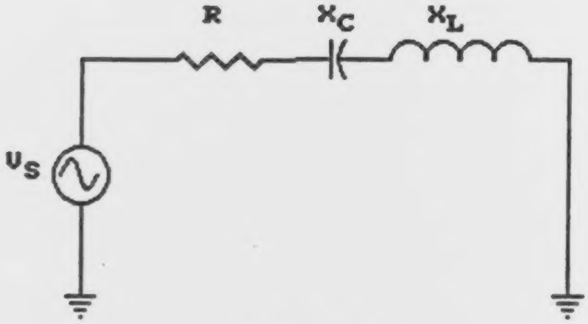

Figure 7

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1. Which of the following is the Thevenin equivalent voltage for figure 6?
   - A. 5.9 V
   - B. 6.8
   - C. 7.7 V
   - D. 8.6 V
   - E. None of the above

2. Which of the following is the Thevenin equivalent resistance for figure 6?
   - A. 13.4 kΩ
   - B. 18.9 kΩ
   - C. 24.4 kΩ
   - D. 29.9 kΩ
   - E. None of the above

3. Which of the following is the Norton equivalent circuit for figure 6?
   - A. I_N 1.07 mA, R_N 18.9 kΩ
   - B. I_N 3.52 mA, R_N 15.3 kΩ
   - C. IN .407 mA, R_N 15.3 kΩ
   - D. I_N 7.37 mA, R_N 18.9 kΩ
   - E. None of the above

4. Which of the following is the Thevenin equivalent voltage and resistance for a battery with an open circuit voltage of 9 V and an output voltage of 5 V with a 100 Ω load?
   - A. 8 V, 13 Ω
   - B. 9 V, 0.2 Ω
   - C. 9 V, 0.8 Ω
   - D. 9 V, 3.2 Ω
   - E. None of the above

5. Which of the following is the time constant for a circuit with a 0.47 μF capacitor and a 12 kΩ resistor?
   - A. 0.03 ms
   - B. 18.3 ms
   - C. 0.235 s
   - D. 5.64 ms
   - E. None of the above

6. In figure 7, if the resistor is 12 Ω, the capacitor is 0.02 μF, and the inductor is 4.5 mH, which one of the following is the resonant frequency?
   - A. 47.3 MHz
   - B. 28.2 kHz
   - C. 16.8 kHz
   - D. 803 Hz

E. None of the above

7. Assume that the voltage source in figure 7 is 3 kHz and the component values are as listed in question 6. Which of the following is the impedance and the angle θ for the circuit in figure 7?
   A. Z 2.57 kΩ, θ 89.7°
   B. Z 12.7 kΩ, θ 38.3°
   C. Z 735 Ω, θ 47.7°
   D. Z 3.14 kΩ, θ 87.2°
   E. None of the above

8. Which of the following is the Q of the circuit in question 6?
   A. 135
   B. 6.42
   C. 7.07
   D. 15.3
   E. None of the above

Unit

B

Semiconductors

B-1: Diodes and Atomic Theory
B-2: Rectifiers
B-3: Filters and Zeners
B-4: Diode Circuit LEDs
B-5: Transistor Theory
B-6: Transistor Switch
B-7: Transistor Bias
B-8: Transistor Ampifiers
B-9: Multistage Transistor Amplifiers
B-10: Oscillators and Feedback
B-11: Voltage Regulation
B-12: Other Types of Transistors
B-13: Thyristors

B-1

Diodes and Atomic Theory

UNIT OBJECTIVE: Upon completion of this instructional unit, the student will be able to demonstrate a knowledge of how semiconductor devices operate and how they are used in a circuit.

SPECIFIC OBJECTIVES: Upon completion of this assignment, the student(s) will be able to demonstrate a knowledge of:

- basic atomic theory
- the basic internal structure of a diode and transistor

TERMS

Germanium: An element that is still used to make diodes and some transistors.

Silicon: An element that is usually found in nature combined with oxygen in the form of silicon dioxide. Silicon dioxide is quartz, and most rocks and sand are made of silicon dioxide. Pure silicon is the most common ingredient in most of the diodes and transistors made today.

Doping: The process of adding impurities to silicon to create either N-type or P-type material.

ATOMIC THEORY

Your study of atomic theory in your Chemistry I course will help you understand how the diode and the transistor are constructed and how the electrons move in the silicon crystal. To help you, we will review some of these principles and then apply them to semiconductors.

The universe is made of something we call matter. Matter is composed of small particles called atoms. Atoms combine to form molecules. Molecules can be in the form of a solid, liquid, or gas. The form it takes is determined by the strength of the bonds between the molecules. There are over 100 different atoms in the universe, and each one represents an element. Silicon, copper, and oxygen are just a few of the elements. Silicon dioxide is a compound formed by the atoms of silicon and oxygen combining together. The term *dioxide* tells us there are two atoms of oxygen combining with each atom of silicon. Silicon dioxide is the chemical name for quartz. Silicon dioxide or quartz is what most of the rocks on this planet are made of. This makes silicon one of the most common elements in nature.

The silicon atom shown in figure 1 has a core or nucleus in the center with 14 protons. The 14 electrons shown circling the nucleus balance the charge of the 14 protons in the nucleus.

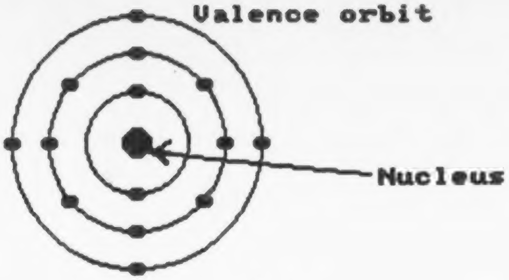
Valence orbit
Nucleus

Fig. 1. Silicon atom

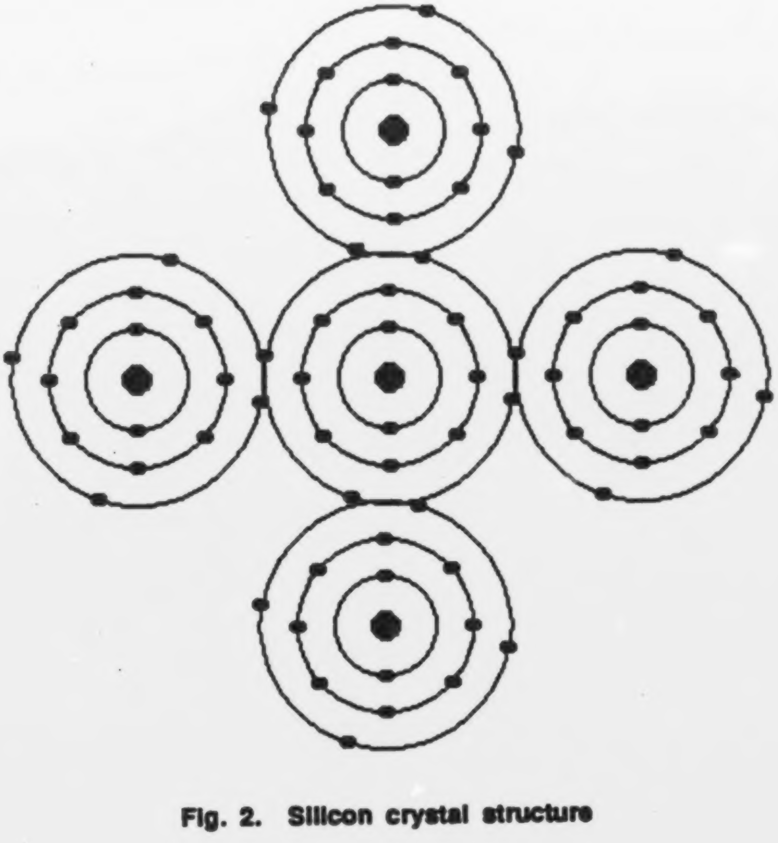

Fig. 2. Silicon crystal structure

The electrons that are orbiting the nucleus have to remain in specific orbits. The silicon atom has two electrons in its inner orbit, four electrons in its second orbit, and four in its outer or valence orbit. Each one of these orbits represents a specific energy level. When an electron moves from one orbit to another, energy will either be gained or lost. The electrons in the outer orbits have the highest energy level. Energy has to be added to the atom before an electron can move from the second orbit in the silicon atom to the valence orbit. If an electron falls back to an inner orbit, the atom will give off energy.

The number of electrons and the number of their orbits will vary for different atoms. For any atom, the maximum number of electrons that can exist in the valence or outer orbit is 8. If an atom has 8 electrons in its outer orbit, it is very stable. A stable valence orbit will not lose an electron to an adjacent atom. The ability of electrons to move from one atom to another results in the flow of current or electricity. Atoms or compounds that have stable valence orbits will not allow current to flow and are called insulators. The silicon atom has four electrons in its outer orbit, which puts it halfway between an insulator and a conductor. Silicon is called a semiconductor. Copper, which is a good conductor, has only one electron in its valence or outer orbit.

SEMICONDUCTOR MATERIAL

When silicon atoms join to form a molecule, they share their four valence electrons. This sharing will result in each atom having the full 8 electrons as shown in figure 2.

In the early days of transistor development, germanium was commonly used as the semiconductor material. Silicon was found to be better suited for making transistors because pure silicon has almost no free electrons at room temperature when compared with germanium.

Current can flow through semiconductor material in two different ways. Electron flow or conduction is the movement of free electrons. The other method is hole current. Hole current results when an outer orbit is missing an electron. The valence electron in the orbit of an adjacent atom is then attracted to the orbit with the missing electron. This attraction causes the electron to jump over and fill the hole. When the electron moves, it leaves a hole behind it. The hole has now moved to the adjacent atom. As other electrons are attracted to the hole, the hole appears to move in the opposite direction to the electron flow. This is called *hole current*. When energy is added to a semiconductor, it will cause electrons to leave their orbits, and we will have both electron flow and hole flow. As each electron leaves its outer orbit, it leaves a hole behind which can be filled by electrons from an adjacent atom. Engineers often refer to electron hole pairs. The Hall effect results when a magnetic force is used to move the holes to one side of the silicon and the free electrons to the other side. A voltage can then be measured that is proportional to the amount of magnetic force that is present. The voltage is measured across the silicon for the Hall effect.

DOPING

A pure piece of silicon does not have enough free electrons for a usable amount of current. Doping is the process of adding impurities to the pure silicon to increase the number of free electrons or holes. To increase the number of free electrons, we can add impurities with five electrons in their valence orbit (see fig. 3).

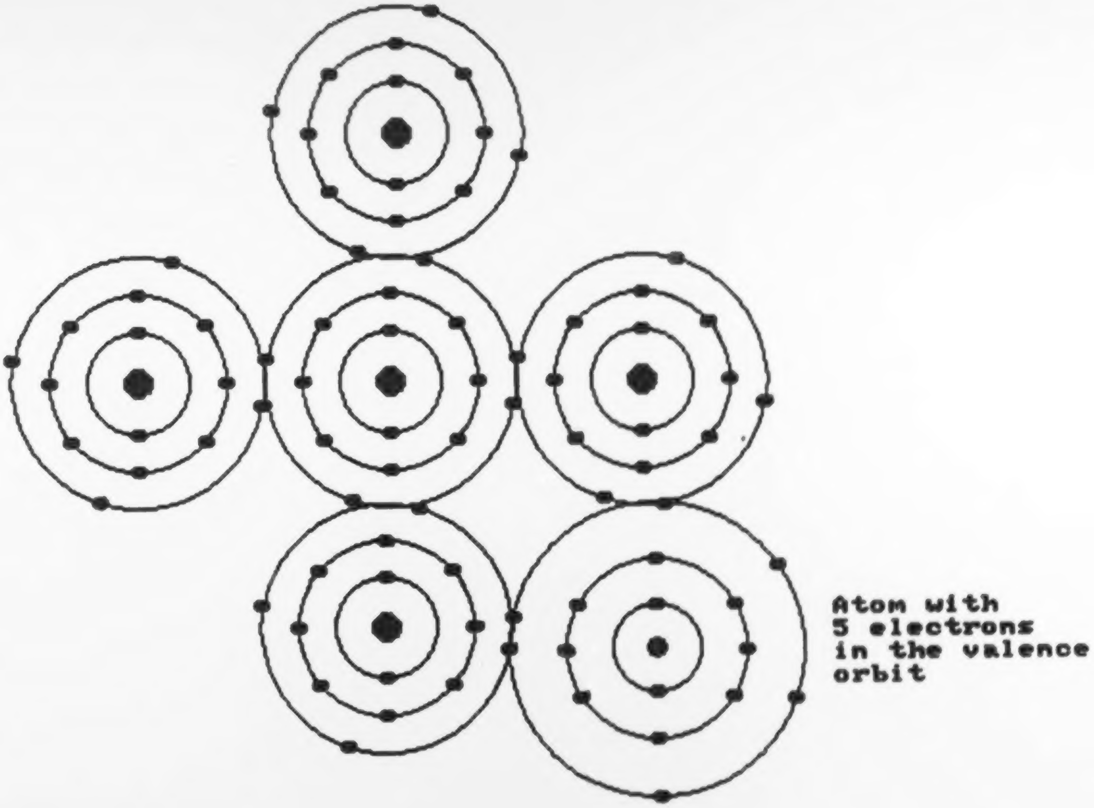
Atom with
5 electrons
in the valence
orbit

Fig. 3. N-type semiconductor

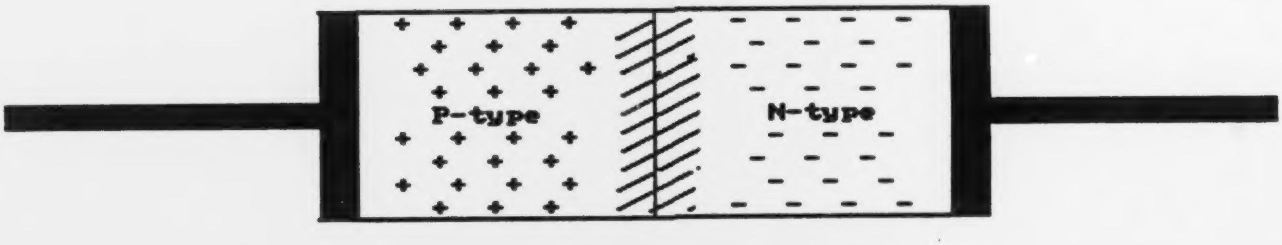
P-type
N-type

Fig. 4. Diode showing the P-N junction

The extra electron or the fifth electron becomes free to travel from atom to atom. This type of material is called *N-type* material. If we add impurities with three electrons in their valence orbit, we will get extra holes. This type of material is called *P-type* material.

Adding these impurities will not create a positive or negative charge to the piece of silicon since all the electrons are balanced with an equal number of protons. The impurity that is added will have the same number of protons as it has electrons. Adding the impurities will result in individually charged particles. There will be extra particles with a positive charge in the P-type material. The particles with the positive charges are called positive ions. The N-type material will have negative ions. Both the N-type and P-type material will now conduct current.

The more doping, or the more impurities that are added to the silicon, the less resistance there will be to the flow of current. This resistance in a doped semiconductor is called bulk resistance. Bulk resistance is proportional to the voltage and current according to Ohm's law.

DIODE

A silicon diode is made by fusing a piece of N-type material to a piece of P-type material (fig. 4). Metal caps are then connected to each end with wires connected to the metal caps.

The area between the two types of material develops special properties. This area is called the *depletion area*. The free electrons from the N-type material are attracted to the holes in the P-type material. They move across from the N-type material to the P-type material and fill the holes. As a result of this movement by the free electrons, the depletion area becomes an area with no electrons or excess holes. It becomes a neutral zone, and it also becomes difficult for electrons to pass through this area. The electrons that are able to move easily through the N-type or P-type material require extra energy to get through the depletion area. This extra energy amounts to 0.7 V. A diode conducting current will have a 0.7 V drop across it. This 0.7 V drop does not depend on the amount of current and, therefore, does not follow Ohm's law. The voltage will change slightly with changes in current because of bulk resistance. This 0.7 V drop applies to any diode junction. As you will learn later, the junction between the base and emitter of a transistor is a diode junction. Variations in the bulk resistance and device will cause variations in this voltage. Typically, the voltage can vary from 0.6 to 0.8 V. We will use 0.7 V as a standard for our calculations to eliminate any confusion.

When we are looking at a diode in a circuit, we can approach it as an ideal diode. The ideal diode will only allow current to flow in one direction, and we would ignore the 0.7 V drop, bulk resistance, and leakage. Most of the time, we will consider a diode in a circuit as having the 0.7 V drop and ignore the leakage and bulk resistance. We can call this our approximate diode. If it is necessary to be very accurate, then we can use our accurate diode and include the bulk resistance and leakage in our calculations.

The 0.7 V drop exists when current is pushed in the forward direction through a diode. When we reverse the voltage or apply a reverse-biased voltage across a diode junction, the depletion area increases and there is no current flow. The depletion area increases in size to match the reverse voltage that is applied to the diode junction. The depletion area gets bigger because the positive terminal is now on the N-type material side and the negative terminal is on the P-type material side. The positive potential attracts the free electrons away from the depletion area, and the negative potential attracts the holes away from the depletion area. The departing electrons leave behind extra holes or positive ions, and the departing holes leave behind negative ions. The extra positive and negative ions contribute to the size of the depletion area. The stronger the potential pulling the electrons and holes away from the depletion area, the larger the depletion area will get. As the voltage varies, the depletion area changes in size.

This change in the size of the depletion area is used to make a diode that changes capacitance with the voltage put across it. The diode does not pass any current, except for a very small amount of leakage, and the depletion area acts like the insulation between the two plates of the capacitor. As the voltage is changed, the space between the plates changes, which will change the amount of capacitance exhibited by the diode. An increase in voltage will increase the distance between the positive potential and negative potential. This results in a decrease in capacitance with an increase in proportion to the capacitance. All diodes operate this way. Some diodes are made to enhance this characteristic and are called *varicap diodes*. Varicap diodes are used in radio receivers to change the capacitance across a tuned circuit. This is the principle behind the automatic frequency control found in most FM receivers.

If the reverse voltage that is applied to a diode junction becomes sufficiently large, the depletion area will break down and allow the current to flow with no resistance except for the bulk resistance. The bulk resistance in most diodes is only a few ohms and has a negligible effect. This sudden rush of current is a result of the free electrons, which are moved by the higher voltage, bumping into other electrons and freeing them also. The sudden rush of current when the voltage causes a breakdown is called the *avalanche effect*, and diodes that are made to enhance this characteristic are often called avalanche diodes. The more common name for this type of diode is the *zener diode*. All diodes have this characteristic. The high currents that can result from this breakdown will destroy the diode if the current is not restricted by some resistance in series with the diode. The zener diode is a very common diode and is used in power supplies and circuits where a voltage reference is needed. The diode will always break down and allow current to flow at the same voltage. This characteristic allows the zener to be used to set up a reference voltage. When you begin to study how a zener diode is used in a circuit, remember to always restrict the current through the diode with some series resistance.

When current is passing through a diode in the normal forward manner, which is called forward-biased, the electrons travel from the N-type material to the P-type material. The free electrons in the N-type material have more energy than the electrons in the P-type material. When the electron drops into the hole in the P-type material, some energy is given off. For an ordinary diode, this energy can be considered heat, and too much heat or current will destroy the diode.

When a diode is made from other materials such as gallium, the energy radiated can be visible light. Gallium will cause radiation in the red spectrum. A diode designed to radiate light energy is called a *light-emitting diode*. Clear plastic is placed over the depletion area to allow the light to radiate out. Because different materials are used instead of silicon, the voltage drop across the depletion areas is different. The typical red LED (light-emitting diode) will have a voltage drop of from 1.5 V to 2.5 V. Most ordinary LEDs will have a maximum current rating of around 20 mA. When we add an LED to a circuit, we will design the LED portion of the circuit based on a 2 V drop across the LED and 15 mA through the LED. Light-emitting diodes do not normally have as strong a light output as a regular incandescent light. The primary advantage of an LED is that it will give off light indefinitely. An LED will also switch on and off very rapidly, which allows it to be used for a variety of signalling and control purposes.

The symbols in figure 5 show the various diodes we have discussed. The lead on the diode feeding into the point of the arrow is often called the *cathode*. The lead on the other side is the P-type material, and the cathode side is the N-type material. For conventional current flow, the direction of current flow is with the arrow when looking at the symbol of a diode. You will remember the symbol for the zener diode if you remember that the bar across the point of the arrow looks like a Z. The varicap diode has the symbol of a capacitor in its symbol, and the LED has the arrows showing the energy released. A photodiode looks like an LED with the arrows pointing into the diode. A photodiode will increase its leakage when there is light falling on its depletion area. It is used as a detector for lasers and other light signals.

GRAPHING THE CHARACTERISTIC CURVES OF A DIODE

In figure 6, we have graphed the characteristic curve of a diode. The circuit used to generate this curve is shown in figure 7. We can start with the voltage source at zero volts, and as we increase the voltage from the source, we graph the voltage drop across the diode and the current through the diode. Notice on the graph that as the voltage across the diode increases to the right of the zero volt point, the current remains close to the 0 mA. There is a little leakage that will increase with the voltage drop across the diode. The current through the diode starts to increase when we pass 0.5 V across the diode. This curve showing the current increasing as the voltage increases at the 0.7 V area is called the *knee* of the curve. As we increase the voltage past the 0.7 V area, the current starts to climb quickly. There will still be a slant to the line as it climbs up because of the bulk resistance of the diode.

Now we can go back to the zero volt point and reverse the voltage polarity and start increasing the voltage again. There is a small amount of leakage, as the voltage increases, until we get to the breakdown area. We have shown this diode with a breakdown at 5 V. Notice the knee of the curve; then the current starts increasing rapidly as the voltage is increased only a small amount. Here again the bulk resistance causes a slight shift from the vertical as the current increases.

EXERCISE: Read each question carefully, and take your time. Use your notebook paper or scrap paper to solve the problems. Round off your answer to the three most significant digits.

1. How many protons does a silicon atom have?
   A. 16
   B. 14
   C. 12
   D. 10
   E. None of the above

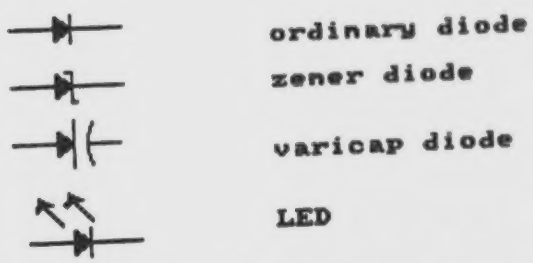
ordinary diode
zener diode
varicap diode
LED

Fig. 5. Schematic symbols for various diodes

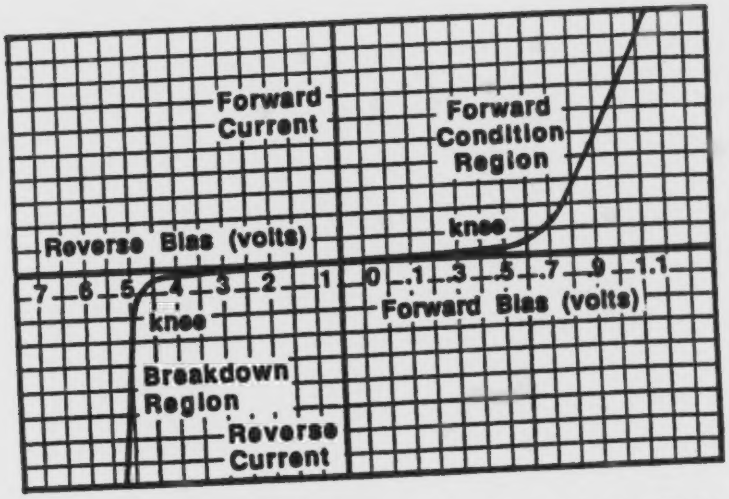

Fig. 6. Typical characteristic curve for a silicon diode

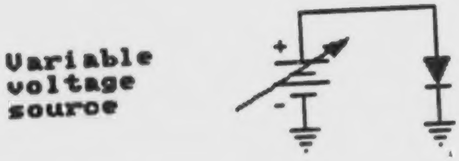
Variable voltage source
+
-

Fig. 7. Diode circuit

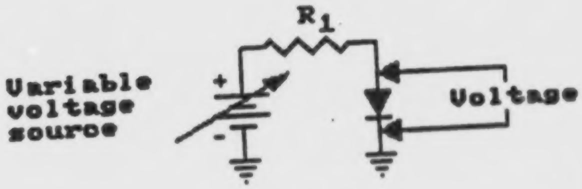
R1
Variable voltage source
+
-
Voltage

Figure 8

2. How much power is dissipated in a diode with the 0.7 V drop and 35 mA of current flowing through it?
   A. 35.6 mW
   B. 24.5 mW
   C. 0.2 W
   D. 1.5 W
   E. None of the above

3. If the voltage coming from the variable supply in figure 8 is 9 V and the resistor R_1 is a [illegible] kΩ, what is the voltage drop across the diode?
   A. 1.3 V
   B. 1.0 V
   C. 0.7 V
   D. 0.4 V
   E. None of the above

4. What is the maximum number of electrons that can be in the outer or valence orbit of any atom?
   A. 32
   B. 16
   C. 8
   D. 4
   E. None of the above

5. How many electrons should be in the outer orbit of material added to silicon to make P-type material?
   A. 3
   B. 4
   C. 5
   D. 6
   E. None of the above

6. How many electrons are in the outer orbit of a good conductor?
   A. 7
   B. 5
   C. 3
   D. 1
   E. None of the above

7. If the variable voltage supply, in figure 8, is 6 V and the resistor is a 1.2 kΩ, how much current is flowing through the diode?
   A. 3.65 mA
   B. 5.0 mA
   C. 5.58 mA
   D. 4.42 mA
   E. None of the above

8. Use the accurate diode to calculate the bulk resistance with 13 mA of current flowing through the diode and a 0.94 V drop across the diode.
   A. 72.3 Ω
   B. 65.4 Ω
   C. 28.5 Ω
   D. 18.5 Ω
   E. None of the above

9. In figure 8, if the voltage source is 9 V and the resistance is 1 kΩ, what would have failed if the voltage drop across the diode is 0 V?
   A. The resistor failed open.
   B. The diode failed open.
   C. The diode was inserted into the circuit backwards.
   D. The resistor increased in value to 10 kΩ.
   E. None of the above

10. A 12 V circuit with a 10 kΩ resistor in series with an LED will result in which condition?
   A. The LED will burn out from too much current.
   B. The 1 mA that passes through the LED is not enough to light the diode.
   C. The LED will glow brightly.
   D. The 12 V is too much voltage across the LED.
   E. None of the above

B-2

Rectifiers

UNIT OBJECTIVE: Upon completion of this instructional unit, the student will be able to demonstrate a knowledge of how semiconductor devices operate and how they are used in a circuit.

SPECIFIC OBJECTIVES: Upon completion of this assignment, the student(s) will be able to demonstrate a knowledge of:

- rectifier circuits
- basic power supply design

TERMS

Sine wave: The sine wave is a basic alternating wave.
Root mean square: This is an ac voltage that is equivalent to the same amount of dc for doing work.

THE SINE WAVE

When you insert an electrical plug into the wall, you are tapping into the power provided by the utility company. This power is always supplied as ac, and the shape of the ac is a sine wave. ***This is the same sine wave you studied in your trigonometry class.*** Most circuitry requires dc and usually at voltages around 12 to 16 V. The power supply is a circuit that is designed to convert the ac from the utility company to low-voltage dc for solid-state circuitry.

Alternating current can be generated by an alternator, which generates the current by spinning a coil of wire in a magnetic field. One complete 360° revolution of the coil will give one complete wave. Notice, in figure 1, how the sine wave is divided into degrees. If we start at the left at 0 and move to the right, this is the same as starting to turn the coil within the magnetic field. At 90° the coil will be cutting the magnetic lines of force at a right angle, generating the maximum voltage. At the 180° point, the coil is reversed and moving with the magnetic lines of force and generating no voltage. As it continues to turn, a negative voltage is generated. The negative voltage peaks at 270°.

We will normally use degrees to identify the part of a sine wave that we are interested in. You can use formula 1 to find the voltage at any instant of time on the sine wave. This voltage is called the *instantaneous voltage*.

$v = V_P \sin \theta$ *formula 1*

Formula 1 is the same formula you studied in your trigonometry class. The only difference is that you are now using voltage instead of undefined units. The formula tells us that if we multiply the peak voltage by the sin of θ, which is the degrees on the sine wave, we will get the instantaneous voltage at that point on the sine wave. The peak voltage is the maximum voltage on the sine wave.

Let's assume that our peak voltage is 10 V. What is the instantaneous voltage at 220°? You will need a calculator to find the answer to this problem. First put the 220 into the calculator and then push the ***sin*** (pronounced "sign") button. The calculator should show -0.643. Next press the multiplication button, enter the 10 V, and push the equal sign. You should have arrived at -6.43 V for the answer. Look at the sine wave in figure 1, and notice that 220° is between the 180° and 360° point. This area of the sine wave is negative, and the 220° point will be at the -6 volt area with a 10 V peak voltage.

You will need to be careful not to confuse the peak value of a voltage with the peak-to-peak value. The ***peak value*** is the maximum voltage that the sine wave reaches. This value is measured from the center of the sine wave or the zero volt line. The ***peak-to-peak value*** is the voltage measured from the positive peak value to the negative peak value, or twice the peak value. The rms value of voltage is an important value that you will use often. The ***rms*** stands for root mean square and is the ac voltage that will do the same work as that amount of dc voltage. Notice where the rms value is on figure 1. Formulas 2 and 3 can be used to find the rms value or peak value of an ac voltage.

$V_{rms} = 0.707\ V_p$ *formula 2*

$V_p = 1.414\ V_{rms}$ *formula 3*

The line voltage coming from the utility company has an ***rms*** value of approximately 115 V. What is the peak value of this voltage? You can use your calculator to multiply 115 times 1.414 for a peak voltage of 163 V.

TRANSFORMERS

In your previous studies of transformers, you learned that a transformer will change the voltage. Most power supplies will use a power transformer that changes the 115 V from the utility company to approximately 12 V. When we are discussing voltage from the utility company and the output from a power transformer, it is assumed that the voltage is ac and rms. If we mean peak or dc, then we will state peak or dc.

Figure 2 shows a transformer connected to an ac voltage source and a load. If there are 10 windings on the primary to every winding on the secondary and the voltage on the primary is 115 V, the voltage on the secondary will be one-tenth of that, or 11.5 V. The voltages on the primary and the secondary of a transformer will follow the turns ratio, or the ratio of windings between the

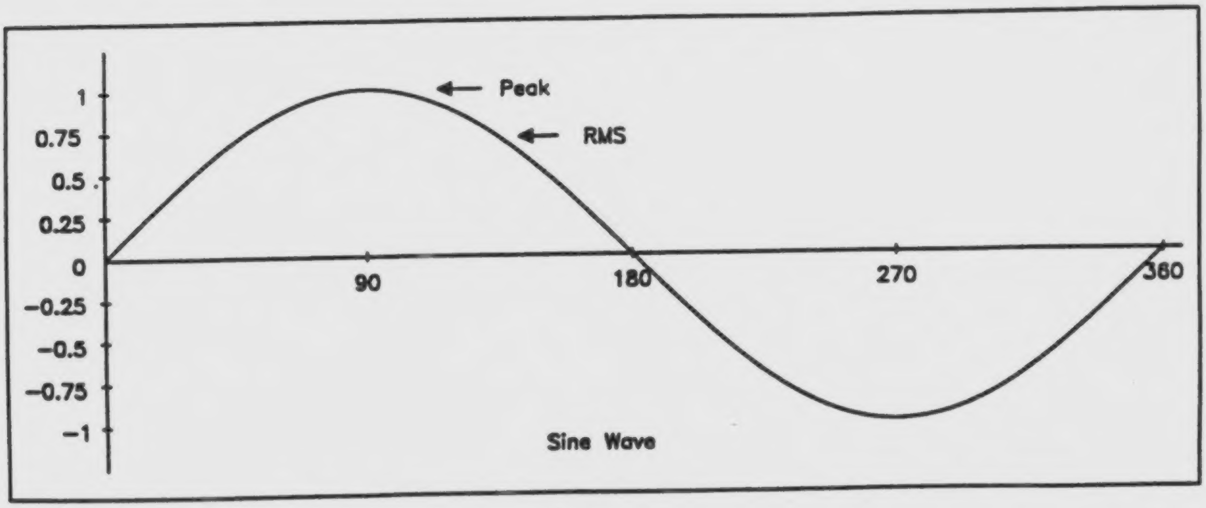

Figure 1

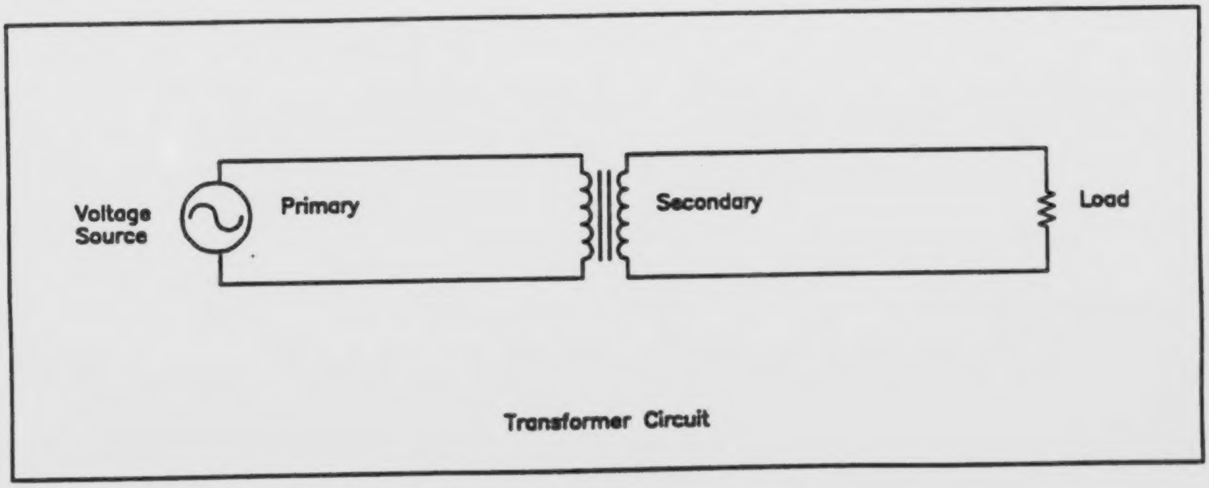
Voltage Source
Primary
Secondary
Load
Transformer Circuit

Figure 2

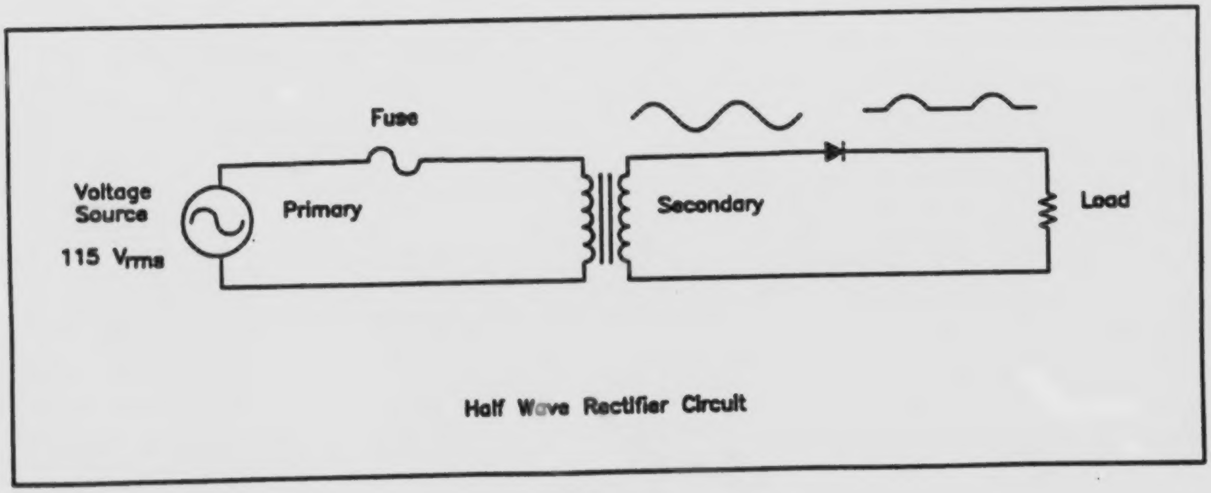
Fuse
Voltage Source
115 V_rms
Primary
Secondary
Load
Half Wave Rectifier Circuit

Figure 3

primary and secondary. The load usually determines the current for the transformer circuit. If the load is drawing 10 mA for a transformer circuit with a 10 to 1 turns ratio, then the primary will have one-tenth of the 10 mA, or 1 mA. If the transformer has no losses, the power in the primary will equal the power in the secondary. Most power transformers are very efficient with low losses.

When a transformer is used in a power supply, it is customary to add a fuse to the primary circuit. A fuse should be oversized to properly protect the circuit. If the primary circuit is drawing 1 mA, as in the previous example, then a 1 mA fuse would not work properly. You should try to pick a fuse size that will allow for the expected variations in the primary current, the type of circuitry that the power supply is driving, and the voltage ratings of the components that the fuse is protecting. A good rule of thumb, which we will use in our following discussions, is to oversize the fuse by an additional one-half. You can multiply the primary current by 1.5 to get this value. Since fuses come in standard sizes, you should round off the value before recording it for the fuse size.

What fuse size would be required for a transformer with a 9 to 1 turns ratio connected to 115 V on the primary and 100 Ω on the secondary? You will need to start by finding the voltage across the load. This voltage will be one-ninth of the 115 V. Use your calculator, divide 115 by 9, and the answer is 12.8 V. Keep the full number in your calculator, and divide that voltage by the 100 Ω for the secondary current. You should have 128 mA of current. The current in the primary will be less than the current in the secondary. Divide the 128 mA by the turns ratio of 9 for the current in the primary 14.2 mA for the primary current. Multiply this by 1.5 to add the extra one-half for the fuse size. You should come up with 21.3 mA, which can be rounded off to 20 mA for the final fuse size.

CHANGING AC TO DC

Notice in figure 3 how we have added a diode to the secondary circuit of the transformer. Remember from your previous studies that a diode conducts current in one direction only. The diode we have added will only allow a positive voltage to appear across the load. If you will look at the sine wave in figure 1, you will notice that the bottom half of the sine wave is negative. The diode will block this bottom negative half of the sine wave. If we turned the diode around, it would block the positive half of the sine wave and allow the negative part of the sine wave to appear across the load. Remember that you can turn the diode around and have a negative voltage across the load as well as the positive voltage. This can be very useful in circuits that we will examine in some later lessons.

The waveforms shown in figure 4 are what you would see on an oscilloscope if you put the probe before and after the diode. Notice on the waveform labeled "rectifier output from diode" that the bottom half of the sine wave is missing. Each of the pulses is connected by a line at the 0 V point. It is not exactly zero because the rectifier diode has a 0.7 V drop across it. This puts the flat portion of the wave at 0.7 V. By clipping off the bottom of the sine wave, we have converted ac to pulsating dc. The output no longer changes polarity; it just varies the voltage. With a 60 Hz input, there will be 60 pulses of output per second. The diode circuit that we have added converts the ac to dc, and the process of doing this is called *rectification*. This circuit is called a half-wave rectifier, and the current rating of the diode must be equal to or greater than the load current. The peak inverse voltage rating is the breakdown voltage, or reverse-biased voltage, that would cause conduction. You studied this as zener voltage in a previous assignment. This peak inverse voltage must be greater than the peak negative voltage, which is sent to the load.

Figure 5 shows a full-wave rectifier circuit. This circuit has two diodes to rectify both halves of the sine wave. Notice the center tap on the secondary of the transformer. The center tap allows each of the diodes to operate on only half of the secondary output. On the positive half of the sine wave, the current flows upward on the secondary of the transformer. Diode #2 will be reverse-biased and block the flow of current. Diode #1 will conduct with the path going through the center tap and not diode #2. This results in only half of the secondary being used for this part of the cycle. The load will see a positive peak of current from this cycle.

When the current reverses for the negative half of the sine wave, diode #1 will be reverse-biased and diode #2 will be forward-biased, sending a positive peak of current to the load again. With diode #1 reverse-biased, the current path will include the center tap and only half of the secondary of the transformer. Only half of the output of the transformer is in use for each half of the sine wave.

If you looked at the voltage across the load with an oscilloscope, you would see a waveform like the one in figure 6. The 60 Hz input that comes from the utility company will result in 120 pulses per second on the output. Twice as many pulses for the full wave would be twice as much current as the half-wave rectifier except that the full-wave only uses half of the transformer secondary. Using half of the secondary cancels the advantage of twice as many pulses for delivering current. The result is that both circuits deliver the same amount of current. The current rating of the diodes in the full-wave circuit can be half the load current since each diode only supplies half of the load current. The full output voltage is across the diodes when they are reverse-biased, so they will still need a peak inverse rating that is higher than the peak output voltage coming from the secondary of the transformer.

THE BRIDGE RECTIFIER

Back in the early days of electronics, silicon diodes were expensive. It was cheaper then to add a center tap to a transformer than supply additional diodes. Today the opposite is true. Silicon diodes are very cheap and transformers are expensive, and adding anything to the transformer like a center tap increases the cost. The bridge rectifier has replaced the full-wave and half-wave as the most common rectifier for power supplies today. This power supply uses four diodes and is more efficient at rectifying the secondary current than the half-wave or full-wave systems.

Figure 7 shows the four diodes as they are normally shown for a bridge rectifier. Notice the ground connection between diodes #1 and #2. With this arrangement, the load will receive only positive pulses. If we turned all of the diodes around, the load would receive only negative pulses.

You can purchase a bridge diode circuit encapsulated in one piece of plastic with four leads coming from it. To identify the leads, a small sine wave is usually placed near the leads for the ac input, and a positive and a negative sign near the leads for the positive and negative output.

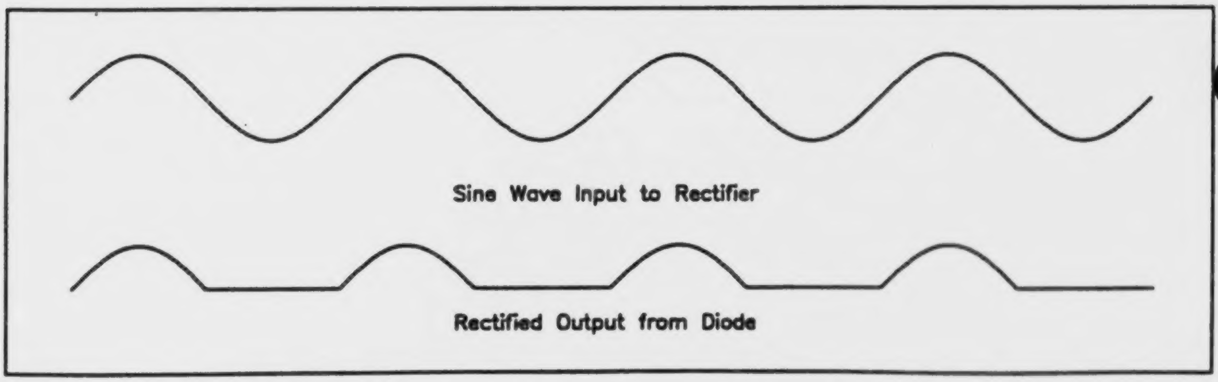

Figure 4

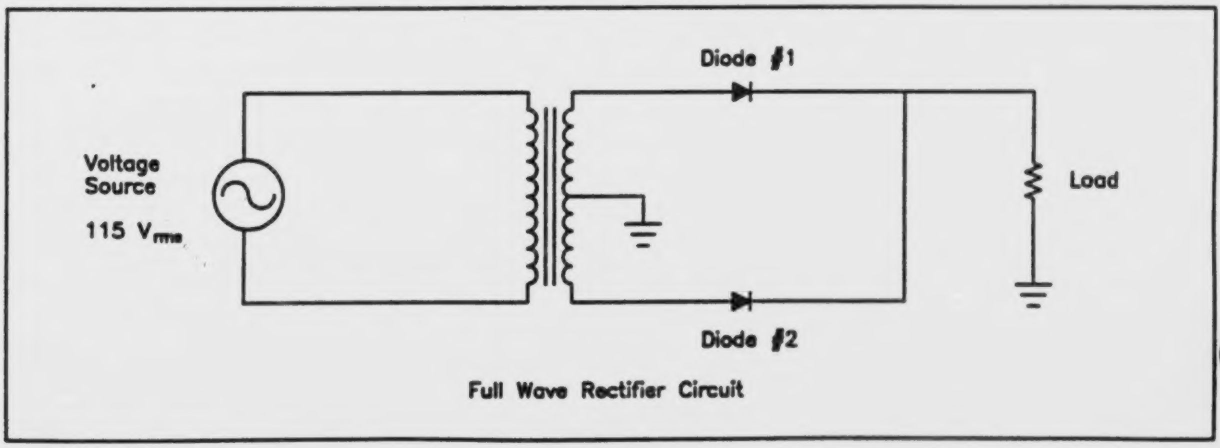
Diode #1
Voltage Source
115 V_rms
Load
Diode #2
Full Wave Rectifier Circuit

Figure 5

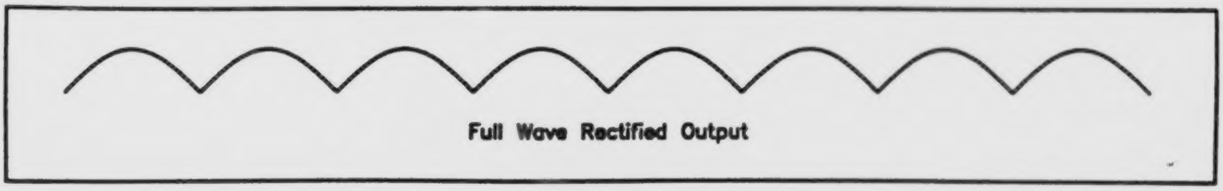

Figure 6

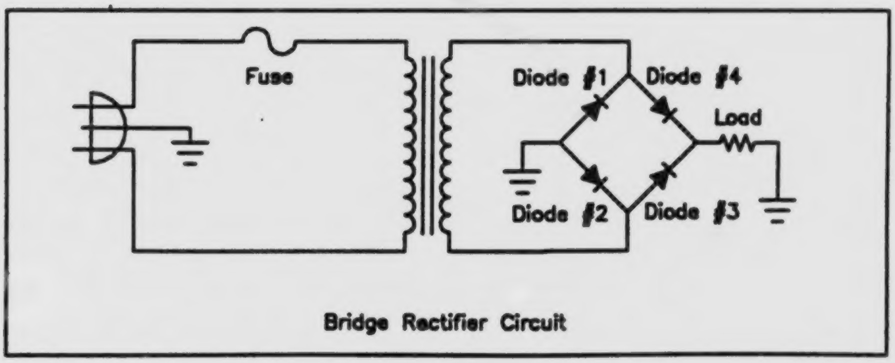
Fuse
Diode #1
Diode #4
Load
Diode #2
Diode #3
Bridge Rectifier Circuit

Figure 7

This circuit uses the full secondary of the transformer, and the current path will include two diodes on both the positive and negative half cycle of the sine wave. The output will have the full peak voltage like the half-wave rectifier and the full current output like the full-wave rectifier.

We can follow the path of the current by starting with the positive half of the sine wave. This will result in the current going up the secondary part of the transformer. The current path will go through diode #4 to the load, and then the return path will take the current from ground through diode #2 and back to the secondary of the transformer. The negative half of the sine wave will follow the opposite path through diode #3 and diode #1. This will result in an output that will look like figure 6.

The voltage on the output will have the full secondary peak voltage minus two diode drops, or 1.4 V. If the secondary of the transformer has a peak output of 16 V, then the peak output on the load will be 14.6 V.

During each half cycle, two diodes will conduct current to the load. The diodes must be rated to handle at least one-half of the load current. The diodes must also be rated to handle the full peak voltage for their peak inverse voltage rating.

What would be the peak voltage across the load, in figure 7, with the input receiving 115 V from the utility company and a transformer with a 9.5 to 1 turns ratio? First use your calculator to find the secondary voltage. Divide 115 by the 9.5 for the secondary voltage. This should yield 12.1 V. Then convert the 12.1 V_{rms} to peak voltage by multiplying it by 1.414. This will give you 17.1 V. The two diode drops will drop the 17.1 V down to 15.7 V. This 15.7 V is the peak voltage across the load.

EXERCISE: Read each question carefully, and take your time. Use your notebook paper or scrap paper to solve the problems. Round off your answer to the three most significant digits.

1. What is the instantaneous voltage at 47° on a sine wave with a peak voltage of 12 V?
   A. 2.28 V
   B. 4.72 V
   C. 6.34 V
   D. 8.78 V
   E. None of the above

2. What is the peak voltage output from a full-wave rectifier that is being driven by 16 V from the secondary of a transformer?
   A. 4 V
   B. 8 V
   C. 12 V
   D. 16 V
   E. None of the above

3. A transformer and bridge circuit is delivering 100 mA to a load. The transformer has an 8 to 1 turns ratio. What size fuse should be specified for the primary of the transformer?
   A. 20 mA
   B. 16 mA
   C. 13 mA
   D. 9 mA
   E. None of the above

4. On a boat, power is often supplied at 400 Hz. What would be the number of pulses per second from a bridge rectifier on this system?
   A. 200 Hz
   B. 400 Hz
   C. 600 Hz
   D. 800 Hz
   E. None of the above

5. What should the peak inverse voltage rating of the diodes in a bridge be if the transformer is connected to the utility and has a 10 to 1 turns ratio?
   A. 24.7 V
   B. 16.3 V
   C. 12.8 V
   D. 8.35 V
   E. None of the above

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B-3

Filters and Zeners

UNIT OBJECTIVE: Upon completion of this instructional unit, the student will be able to demonstrate a knowledge of how semiconductor devices operate and how they are used in a circuit.

SPECIFIC OBJECTIVES: Upon completion of this assignment, the student(s) will be able to demonstrate a knowledge of:

- capacitor filter circuits
- zener circuits

TERMS

Load regulation: Variations in the load current will cause variations in the supply voltage. These variations in voltage when expressed as a percentage are called the load regulation.

Ripple: Ripple is small variations in voltage that exist after filtering. The ripple is the pulsating voltage from the rectifier that has not been filtered out.

THEVENIN EQUIVALENT CIRCUIT

A rectifier is used to convert ac to pulsating dc. In previous studies, you learned how a rectifier circuit can be connected to a transformer to change the ac to a series of pulses. This series of positive pulses is not suitable for supplying power to a radio or most other electronic circuits. A series of pulses can be used to operate a motor or charge a battery. Before this series of pulses becomes useful for electronic circuits, we need to filter and regulate it. Filtering is a process that reduces the rapid voltage variations or smooths out the ripple, and voltage regulation will hold the voltage to a specific amount. Voltage regulation is important to maintain a constant voltage with changes in the load and in the original supply voltage. A good regulator will also filter the voltage.

A complete power supply will consist of a filter to smooth out the dc pulses from the rectifier and a regulator to hold the voltage steady with changes in the load. We will study the capacitive filter and the zener which are used in regulator circuits. The addition of capacitive filters and zener regulator circuits will reduce the output impedance of a power supply circuit.

In figure 1, we have the Thevenin equivalent circuit for a power supply. The series resistance will cause the output voltage to change with changes in the load. As the load becomes lower in resistance and draws more current, the voltage drop across the series resistance will increase. This increase in the voltage drop will result in less voltage at the load.

This series resistance is the output impedance of the power supply circuit. A better power supply will have a lower series resistance. The ideal voltage source would have no series resistance. Ideal voltage sources do not exist in the real world. ***The concept of ideal voltage sources is a mathematical concept. Your algebra and trigonometry courses have shown you the difference between an ideal and a real concept.***

The diodes in the rectifier circuit will increase the series resistance through their bulk resistance. Notice, in figure 1, what the voltage will be across the load at different levels of current and at different values of series resistance. Take some scrap paper and compute the voltage across the load with a voltage source of 12 V and different series resistances. Use series resistances of 1 Ω, 10 Ω, 100 Ω, and 1 kΩ. Compute the voltage across the load with a load resistance of 10 Ω and 1 kΩ for each value of series resistance. This exercise should clearly show you how a low series resistance or low output impedance can keep the voltage output from changing excessively.

FILTERS

Using a capacitor after the rectifier is the most common method of smoothing out the dc pulses from a rectifier. Figure 2 shows a capacitive input filter after the bridge rectifier.

If we were to remove the capacitor from the circuit in figure 2, then the drawing of the waveform in part A of figure 3 would show the waveform that would be sent to the load. Part B of figure 3 shows what the capacitor does to the waveform superimposed on the waveform in part A. The capacitor charges as the voltage increases and feeds current to the circuit as the voltage decreases. The final result is the waveform shown in part C in figure 3.

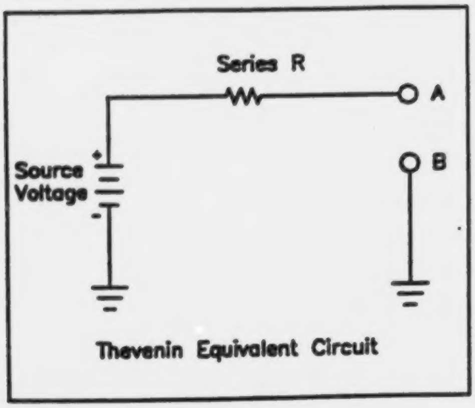
Notice that there still is a small amount of ripple left in the final waveform. The amount of ripple that will be left in the waveform depends on the amount of filter capacitance and the amount of current taken by the load as well as the frequency of the incoming pulses.

$$V_{rip} = \frac{I}{fC}$$ *formula 1*

You can find the peak-to-peak ripple voltage using formula 1. I is the load current, f is the frequency of the pulses which are twice the frequency of the incoming signal for a bridge circuit, and C is the capacitance of the filter capacitor.

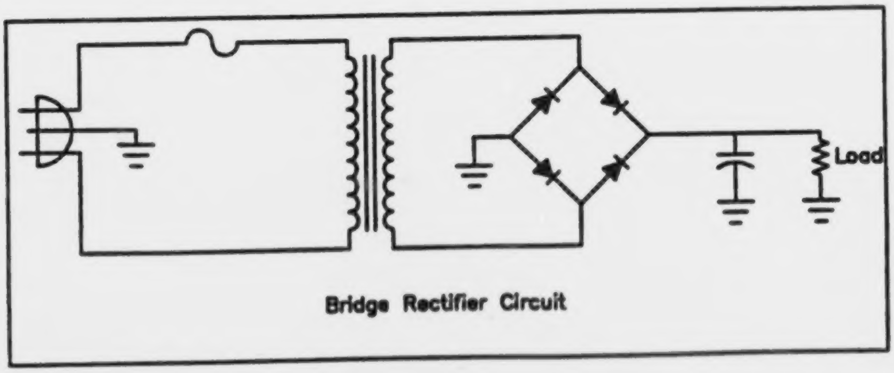
Find the peak-to-peak ripple voltage with a capacitance of 1,000 μF, a current of 30 mA, and a power supply (plugged into the wall) of 60 Hz. Use your calculator to multiply the frequency of 120 Hz times the capacitance of 40 times 10^{-6}. The frequency is 120 because the bridge rectifier will send twice as many pulses to the load as the original frequency fed into it. The result of the frequency times the capacitance is then divided into the current for the final answer. Your answer should be 0.25 V for the peak-to-peak ripple voltage.

Formula 1 is only useful for small values of ripple voltage. If you are designing a power supply and wondering what size of capacitor to pick for the filter, remember that the bigger the better. The time constant of the capacitor and the series resistance should be much longer than the


Series R
A
B
Source Voltage
+
-

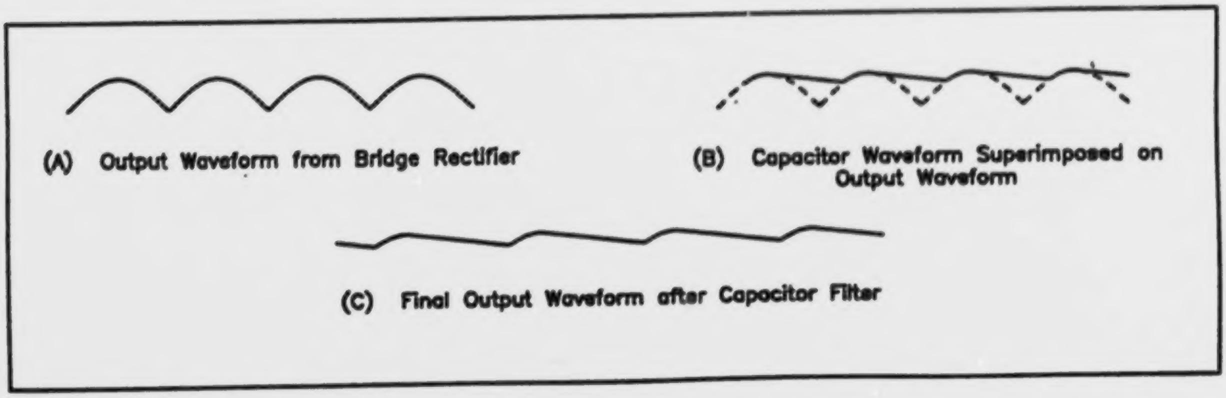
Thevenin Equivalent Circuit

Figure 1



Bridge Rectifier Circuit

Figure 2



(A) Output Waveform from Bridge Rectifier

(B) Capacitor Waveform Superimposed on Output Waveform

(C) Final Output Waveform after Capacitor Filter

Figure 3

period of the pulses to be effective. If the capacitor is too small, it can charge and discharge at the same rate as the pulse is rising and falling. This would result in no real change to the incoming pulses. As the current increases, more capacitance is needed to rapidly charge and discharge to maintain a constant filtered voltage with minimum ripple. The primary consideration for holding the size of a capacitor down is the cost of the capacitor and the physical size of larger capacitors.

The ripple can be reduced by adding a more complex filter network instead of just a capacitor. Figure 4 shows the schematic of two types of pi filters. The filter with the capacitors and choke will be more effective than the resistor. The resistor will be cheaper and take up less room in a circuit. This type of filter system was common before regulators became more common in power supplies. The pi filter is still used if the circuitry needs to be protected from voltage spikes in the line. Voltage spikes can be caused by other equipment switching on and off and by lightning strikes. High voltage spikes can destroy solid-state transistors and integrated circuits, which make up many regulators.

Power supplies with large filter capacitors can occasionally have a problem with surge current. When a power supply is turned off, the filter capacitor will drain off and become completely discharged. The moment the power supply is turned on, this discharged capacitor will appear like a short. This results in a surge of current to the capacitor. This surge can be high enough for the larger capacitors to damage the rectifier diodes and blow the fuse. Since the duration of this surge current is small, the problem can usually be fixed by putting in diodes with higher current ratings and replacing the ordinary fuse with a slow-blow fuse. If this does not fix the problem, then a small resistor in series with the rectifier and between the rectifier and capacitor will limit the initial surge of current. This resistor will also add to the output impedance and should not be used if it is not necessary.

REGULATOR

If you were going to use the power supply in figure 2 to provide power for a radio or audio amplifier, it would be important to have enough filtering to keep the ripple at a minimum. A better solution to the problem is to add a regulator. A regulator can do a good job of filtering the final output from the filter if the power it receives has ripple that is 10% or less than the dc level that it is receiving. The regulator will work with as much as 20% ripple from the filter, but 10% is a better limit to work with. A 12 V dc voltage coming from the filter should have less than 1.2 V peak-to-peak of ripple, although 2.4 V peak-to-peak will be acceptable.

Formula 2, which is the same as formula 1 except that it solves for the capacitance instead of the ripple, can be used to find the minimum capacitance needed for a power supply. This formula will work better with larger amounts of ripple than formula 1.

$$C = \frac{I}{fV_{rip}}$$ *formula 2*

ZENER

In the previous assignment, you learned about the breakdown region of a diode. You can operate a diode in the breakdown region by reverse-biasing it and increasing the voltage to the breakdown point. All diodes have a point where they will go into breakdown. The zener diode is made to take advantage of this breakdown region. The manufacture of the zener diode can control the voltage at which breakdown occurs. This is done by changing the doping that goes into the zener. Breakdown voltages as low as 2 V on up to over 200 V can be achieved.

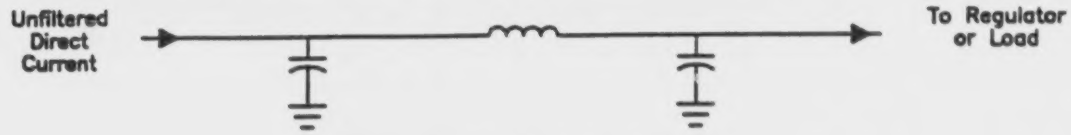
Figure 5 shows the schematic symbol for a zener to the left and the equivalent circuit for a zener on the right. Notice the jagged line across the point of the arrow on the schematic symbol. This jagged line represents the letter "Z," which stands for the word zener.

In a previous assignment, we talked about ideal, approximate, and accurate diodes. We can use the same terms to discuss the zener diode. The ideal zener diode could be represented by the voltage source reverse-biased with no resistance in series. When the voltage across the diode exceeded the breakdown voltage, then current would flow. The voltage could not pass the breakdown voltage because the diode would allow an unlimited amount of current to flow. The approximate diode will include the resistance in series, which is the bulk resistance of the diode. Once current starts to flow in the breakdown region, the small amount of bulk resistance will result in a voltage drop across the diode, which increases with increases in current. Finally, the accurate diode will include the leakage of the diode. There is a small amount of current flow before the diode goes into breakdown, which is the leakage. There is also a small curve when the voltage first enters the breakdown region.

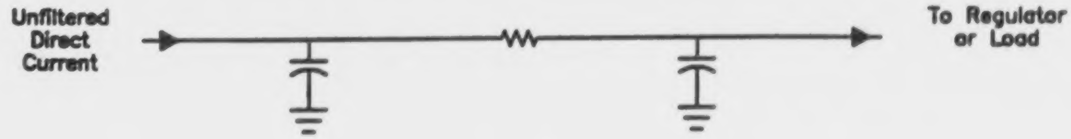
Figure 6 shows a slight curve as the voltage approaches the breakdown region. There is a slight tilt of the line as it goes down, showing the increase in current. The tilt of the line is too small to see on this graph. The schematic, to the right of the graph, shows a circuit that can be used to find the load line, which crosses the curved line of the diode. The curved line is called the characteristic curve of the diode. This line was generated in the same manner as the characteristic curve discussed in a previous assignment.

The load line is used to graph the circuit with that particular diode in it. Notice that the diode is reverse-biased in figure 6. The characteristic curve shows that the diode is a 10 V zener. Notice the 14 V source voltage. To find each of the ends of the load line, we find the extreme points. First we find the voltage point on the load line when the current is zero. If the current is zero, then the voltage would be at its maximum, or in the case of our example, it will be 14 V. Next we find the current with the voltage at 0 V across the diode. This amount of current, according to Ohm's law, is equal to the 14 V source divided by the 1,750 Ω resistance. Now when we connect the two extreme points with a straight line, we have the load line. The point where the load line crosses the characteristic curve is called the Q point. The Q point is the operating point. The actual voltages and current through the diode can be found at the Q point.

If we change diodes in this circuit, which will result in a new characteristic curve, there will be a change in the location of the Q point. If the second diode is a 10 V zener as well, the Q point will not change very much.


Unfiltered
Direct
Current
To Regulator
or Load

Pi Filter Using a Choke and Capacitors


Unfiltered
Direct
Current
To Regulator
or Load

Pi Filter Using a Choke and Resistors

Figure 4

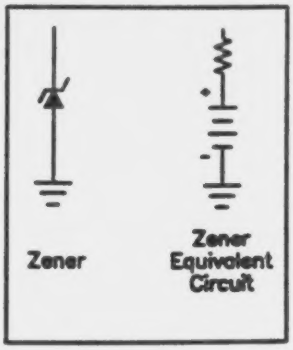

+
-
Zener
Zener
Equivalent
Circuit

Figure 5

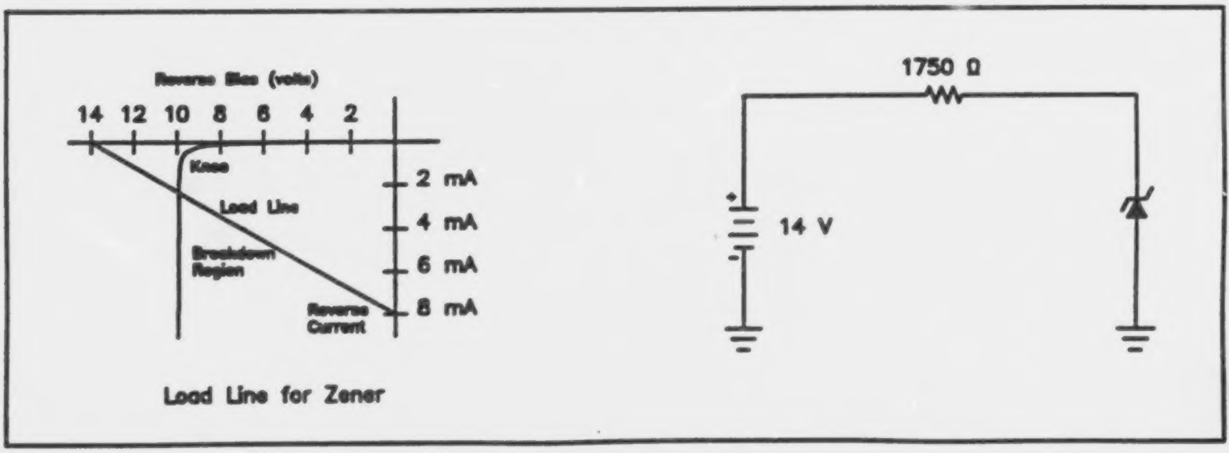

Reverse Bias (volts)
14
12
10
8
6
4
2
Knee
Load Line
Breakdown
Region
Reverse
Current
2 mA
4 mA
6 mA
8 mA
Load Line for Zener
1750 Ω
+
14 V
-

Figure 6

The circuit that we used to generate the load line has a 1,750 Ω series resistance to limit the current through the zener. If this zener was capable of handling 1 amp of current, what is the lowest value series resistance that we could put in place of the 1,750 Ω resistance? Remember that the zener will have 10 V across it. We will use the ideal diode for our calculations. With 14 V coming from the voltage source and 10 V across the zener, this leaves 4 V across the series resistance. The resistance that will give us 1 amp is equal to the 4 V divided by the 1 amp, or 4 Ω. Should you forget to add some series resistances to a zener circuit, you can see that the large amount of current that will pass through the zener will destroy it.

Remember that a zener must always have a current-limiting resistor. When designing a zener circuit, you must also consider the dropout point. The current that is going through the zener in figure 6 is the 2 V divided by the 1,750 Ω, or slightly over 1 mA. If you added a load to this circuit in parallel with the zener which required 2 mA at 10 V, then there would be no current left for the zener. This load that requires 2 mA would be a 5 kΩ resistance. If you look at the 5 kΩ and the 1,750 Ω as a voltage divider, the voltage at the zener will be less than 10 V and the zener is effectively not in the circuit. This is called *dropout*. A load can start to draw enough current to cause the voltage to drop below the zener voltage in a power supply. When this happens, the zener part of the circuit will no longer be controlling the voltage or reducing the ripple in our circuit.

We have taken the basic power supply circuit in figure 2 and added a zener with the series resistance for figure 7. The added zener circuitry gives us a regulated power supply circuit. One of the disadvantages of using a zener in a power supply circuit is the requirement for the series resistance. The zener must have something to limit the current through it. Let's assume that we are going to design this power supply, in figure 7, from the beginning. To begin with, we need a set of requirements or specifications. Our requirements can be that our load or the equipment that needs the power supply will require 6 V and 50 mA.

In the schematic we show the load as a resistor. Remember that you do not usually build a power supply to simply heat up a resistor. We use the symbol of a resistor as an equivalent circuit for the actual load, which could be anything. The first component that we will need to consider is the transformer with a secondary voltage around 6 V. Remember, that the secondary voltage of a transformer is considered to be ac rms unless we specify otherwise. This 6 V rms is rectified by the bridge circuitry into pulses with a peak value of 8.5 V minus the 1.4 V drop across the two diodes in the bridge circuit. This leaves us with a peak of 7.1 V. The capacitor filters these pulses and gives us relatively clean dc at approximately the 7.1 V level. What we have is 7.1 V of dc with a small amount of ripple feeding into R_S and the zener circuitry. We need 6 V across the load. The 6 V zener, which is in parallel with the load, will give us the 6 V at the load. The voltage drop across R_S is now the 7.1 V minus the 6 V, or 1.1 V. We needed 50 mA supplied to the load which will go through R_S. The value of R_S is ideally 1.1 V divided by 50 mA, which gives 22 Ω. There is a problem with this value for the resistance. First, the resistor has 5% tolerance, and, second, we need some current in the zener for it to operate. Also, there is a little ripple on the 7.1 V.

A good rule of thumb is to calculate the resistor value as we have done and then pick the next whole resistor value lower than that. Remember, resistors come in specific values. The next lower value in resistance from 22 Ω is 20 Ω; however, we need to go a whole value lower. Pick the 18 Ω resistor for R_S. With the 18 Ω resistor in place, let's examine the circuit. We still have

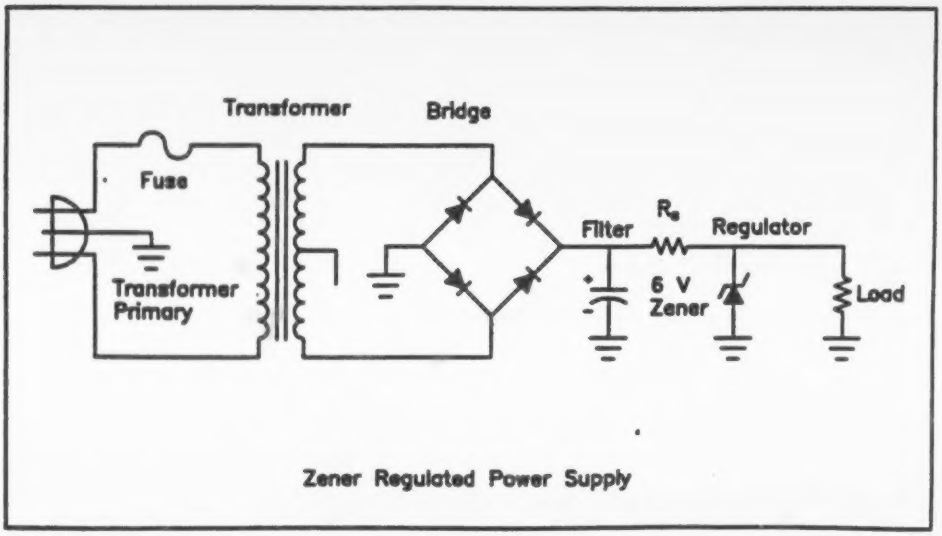

Transformer
Bridge
Fuse
Filter
R_s
Regulator
Transformer Primary
6 V Zener
Load
Zener Regulated Power Supply

Figure 7

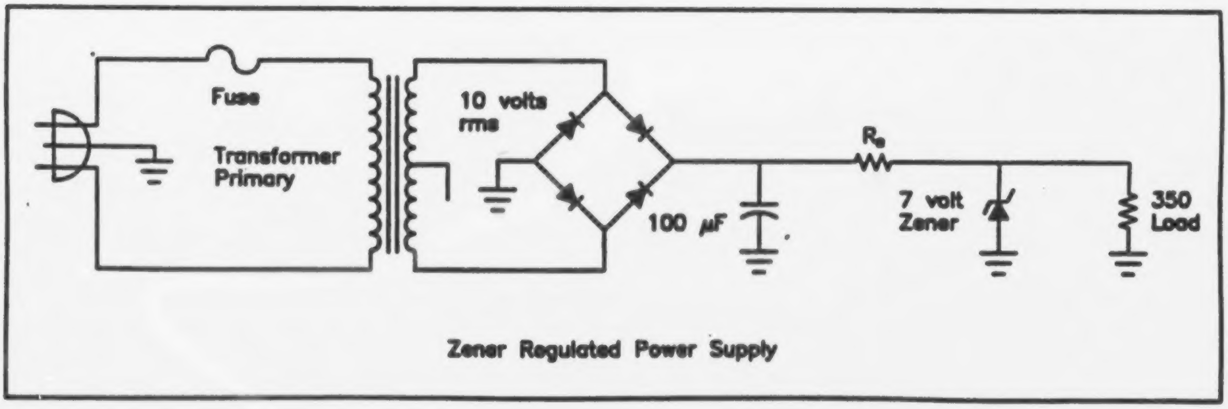

Fuse
10 volts rms
Transformer Primary
R_s
100 μF
7 volt Zener
350 Load
Zener Regulated Power Supply

Figure 8

7.1 V feeding the 18 Ω resistor, and 6 V across the zener. This gives the 1.1 V drop across the 18 Ω resistor. Our load only takes 50 mA of current. So, 1.1 V divided by 18 Ω gives 61 mA of current going through the 18 Ω resistor. The 61 mA minus the 50 mA that goes to the load leaves 11 mA of current going through the zener. This 11 mA of current is sufficient to operate the zener far enough from the knee to hold the voltage solid at 6 V. To complete this power supply we would need to include a fuse. Use the 61 mA for the secondary current when calculating the fuse size. The voltage on the primary can be assumed to be 115 V_{rms}. The standard voltage that we can expect from the utility company is 115 V. This 115 V divided by the 6 V will give a turns ratio of 19.2 to 1. The primary current can be obtained by dividing the 61 mA of secondary current by the 19.2 turns ratio for 3.2 mA of primary current. Add 50% to this for the fuse size, round off the value, and put a 5 mA fuse in the circuit. We would use a zener regulator only in a small power supply. Surge current is occasionally a problem in the bigger power supplies. If the surge current does blow the fuse, we can change it to a slow-blow fuse. This type of fuse will require that the current, which is necessary to blow it, last long enough to heat it. A very short burst of current, which is usual with surge current, will not normally take out a slow-blow fuse.

If this power supply had 15 V_{rms} on the secondary and a 12 V zener to supply 150 mA to the load, what size resistor would you recommend for R_S? First find the peak voltage from the 15 V_{rms} and subtract the 1.4 V diode drop from it. Keep these numbers in your calculator as you work. Subtract the 12 V from the zener to find the voltage across R_S. Then divide this voltage by the 150 mA of current that is required by the load. Pick a resistor value that is below the calculated value to compensate for the variations in resistor value and voltage fluctuations. You should have picked a resistor value of 47 Ω.

EXERCISE: Read each question carefully, and take your time. Use your notebook paper or scrap paper to solve the problems. Round off your answer to the three most significant digits.

1. What size fuse should be specified for the circuit in figure 8?
   A. 0.9 mA
   B. 1.7 mA
   C. 2.2 mA
   D. 2.7 mA
   E. None of the above

2. What value resistor should be specified for R_S in figure 8?
   A. 180 Ω
   B. 240 Ω
   C. 330 Ω
   D. 470 Ω
   E. None of the above

3. A technician built a large power supply that blows the fuse every time it is turned on. What might be the problem?
   - A. The load is not connected to the power supply.
   - B. The filter capacitor has failed open.
   - C. The sudden rush of current to fill the discharged capacitor is blowing the fuse.
   - D. The value of R_S is too high.
   - E. None of the above

4. How much ripple is being fed into R_S from the filter capacitor in figure 8?
   - A. 3.62 V
   - B. 3.07 V
   - C. 2.35 V
   - D. 1.67 V
   - E. None of the above

5. If R_S is 100 Ω, how much current is flowing through the zener?
   - A. 120 mA
   - B. 37.4 mA
   - C. 8.62 mA
   - D. 2.35 mA
   - E. None of the above

B-4

Diode Circuit LEDs

UNIT OBJECTIVE: Upon completion of this instructional unit, the student will be able to demonstrate a knowledge of how semiconductor devices operate and how they are used in a circuit.

SPECIFIC OBJECTIVES: Upon completion of this assignment, the student(s) will be able to demonstrate a knowledge of:

- voltage multipliers
- light-emitting diodes

TERMS

LED: The letters LED stand for light-emitting diode. This diode is used to give off light. It is used in displays, as an indicator, and as a source for ultraviolet light.

Voltage multiplier: The voltage multiplier is a diode and capacitor circuit, which will give a dc output that is a multiple of the peak ac voltage input.

LIGHT-EMITTING DIODE

Until the light-emitting diode (LED) was developed, the primary source for light was the incandescent bulb. Light is generated in an incandescent bulb when the filament is heated by current flowing through it. Although a variety of things can be done to increase the life of a light bulb, it still will only provide light for a specific period of time. The filament of an incandescent bulb is used up during the process of providing light. The light-emitting diode does not have this problem. It will, theoretically, provide light for an indefinite period of time.

When current is passed through a diode in the forward direction, the diode will give off energy. ***Your studies in physics have taught you about energy.*** This energy is usually in the form of heat. By changing the materials that are used to make the diode, we can obtain light as the energy that is radiated.

A diode will give off energy as a result of the electrons moving from the higher energy state in the N-type material to the lower energy state in the P-type material. When the electron drops into a hole or combines with the positive ion, in the P-type material, it will give off energy. ***In your physics class, you learned about the behavior of electrons as they orbit the atom's nucleus.*** Silicon is used to make most diodes. Silicon is opaque, which means it will block any light energy that is radiated. Light-emitting diodes are often made from arsenic, gallium, and phosphorus. The type of material that is used will determine the frequency of the radiation.

The coating around the junction of an LED can be either clear or colored the same color as the light that is radiated. The LED package can be a simple chip that is designed to mount on a printed circuit board or a complex collection of LEDs that are designed to display numbers and letters. Red LEDs are brighter than LEDs of other colors, which makes the red LED the most popular.

Diodes made from silicon have a 0.7 V drop across their depletion area. The common red LED will have from 1.5 V to 2.5 V drop across its depletion area. According to manufacturer's specifications, most of the common red LEDs have a maximum current limit of 20 mA. When we use an ordinary LED in a circuit in this lesson or any of the following lessons, we will use the design rule of designing for a 2 V drop across the LED and 15 mA of current through the LED. If you are aware of different parameters for the LED that you are using, then do not follow this design rule. This rule will normally result in a little less than maximum current and approximately in the center for voltage.

Notice the LED circuit on the left in figure 1. There is a voltage source, a series resistor to limit the current through the diode, and the LED. The LED is forward-biased by the voltage source. If the voltage source in figure 1 is 8 V, what should the resistance in series be, to properly limit the current? Our design rule says the LED has a 2 V drop across it. According to Kirchhoff's voltage law, the voltage drop across the LED and the series resistor will equal the voltage from the voltage source. Mathematically, we can find the voltage drop across the series resistance by subtracting the 2 V across the diode from the 8 V source. This will leave 6 V across the resistor. Our design rule states that 15 mA will pass through the diode. The resistor is in series with the diode; therefore, the 15 mA will also pass through the resistor. We now have 6 V across the resistor and 15 mA through it. We can use these values to calculate the resistance of the series resistance. The 6 V divided by the 15 mA will give us 400 Ω. There are no 400 Ω 5% resistors. The closest 5% value to 400 Ω is 390 Ω.

Figure 1 shows the drawing of the seven-segment LED display indicator. Each one of the straight lines is one LED. This display is used for numbers and some letters. The letters A through F are needed for a numbering system called hexadecimal. You will study the hexadecimal system later in this course. This type of display will have a problem with the capital letters D and B. The same segments will light for the capital letter D and for the number 0. Also, the number 8 and the capital letter B will light the same segments. When these letters are needed, it is common practice to use the lowercase letters instead. This same display system is used with both LED displays and LCD displays. LCD stands for liquid crystal display. The liquid crystal display has become more popular than the LED systems. You will learn more about the LCD system in a later assignment.

The seven-segment display requires a current-limiting resistor for each diode or segment. This is shown in figure 1. Notice how the design of the display connects all the diodes at one end. This results in seven pins coming out for the diodes and two pins that are connected in common with the other ends of the diodes. When you are replacing a seven-segment display, it is important to pick either a common anode or common cathode display. The type of display will determine the direction of the flow of current. If you pick the wrong type of display, all the LED diodes will be reverse-biased.

VOLTAGE MULTIPLIERS

The schematic in figure 2 is a circuit that can be used to provide a dc voltage equal to twice the peak ac input voltage. It is called a voltage doubler. This type of circuit is often used to double or triple the voltage from a high-voltage transformer to a computer or TV monitor. The circuit is not capable of supplying very much current to the load. The picture tube in a video monitor does not require much current.

To understand how the circuit works, we can start with the negative part of the sine wave feeding into the circuit. This will charge C_1 to the peak voltage of the source. The current to charge C_1 goes through diode D_1. When the polarity changes, the positive output from the voltage source is in series with C_1 feeding through D_2 and charging C_2. This puts the voltage source and C_1 in series to provide twice the peak value of the voltage source charging C_2. C_2 is then in parallel with the load. This circuit is sometimes called a half-wave doubler. The ripple that is left on the output will be the same frequency as the input.

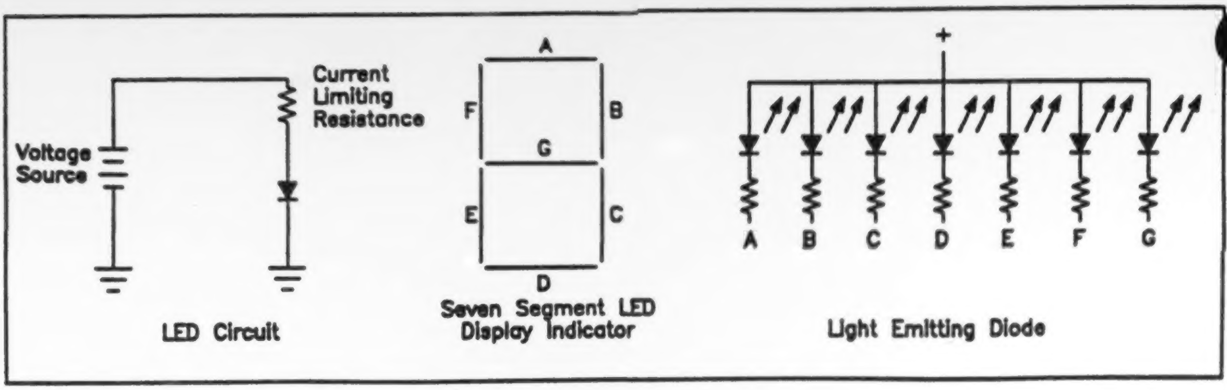
The circuit in figure 3 is a full-wave voltage tripler, with three sections. This circuit will provide three times the peak input voltage to the load. Capacitors C_1 and C_2 are first charged to the peak voltage of the source. Then C_3 is charged to a voltage equal to double the voltage of the source. This voltage across C_3 is a result of C_1 being in series with the source. The capacitor C_3 is at double the source voltage, and the capacitor C_1 is at the source voltage. The two capacitors are in series for a total of three times the source voltage. Additional stages can be added to this circuit for higher voltage outputs. The voltage level of the ripple will increase as more stages are added.

TRANSIENT SUPPRESSION

Sudden voltage surges can be a major problem for electronic equipment. These voltage surges come from other electronic equipment switching on or off and from lightning. Lightning can cause the voltage to increase dramatically on an ordinary 115 V ac line. The voltage may climb to tens or hundreds of thousands of volts. Usually the voltage increase will resemble a spike. This means the voltage is only that high for a few microseconds before dropping back to normal. Those few microseconds are enough to destroy delicate solid-state equipment.

A strong voltage spike coming into a transformer will be suppressed, but not eliminated. If the spike was strong enough, there will be sufficient voltage left to damage the circuitry that follows the transformer. The transient suppressor is designed to reduce the initial voltage level to a point where the transformer and filter circuitry will be able to handle the spike that remains.

There are many types of voltage suppressors. A common lightning suppressor on telephone lines feeding into electronic equipment is simply two plates close together. This will allow the high voltage to spark across the gap to ground. The lower telephone voltages see this gap as an open, which has no effect on the circuit. Another popular system uses loosely packed carbon granules

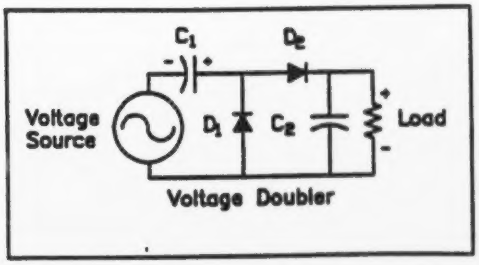

Voltage Source
Current Limiting Resistance
A
B
C
D
E
F
G
+
A
B
C
D
E
F
G

LED Circuit

Seven Segment LED Display Indicator

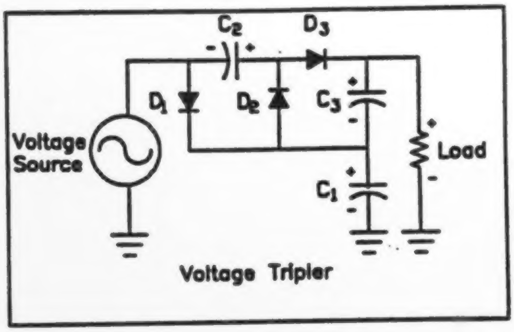
Light Emitting Diode

Figure 1


C_1
D_2
Voltage Source
D_1
C_2
Load
+
-

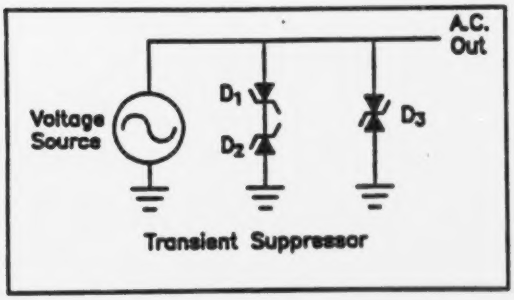
Voltage Doubler

Figure 2


C_2
D_3
Voltage Source
D_1
D_2
C_3
Load
C_1

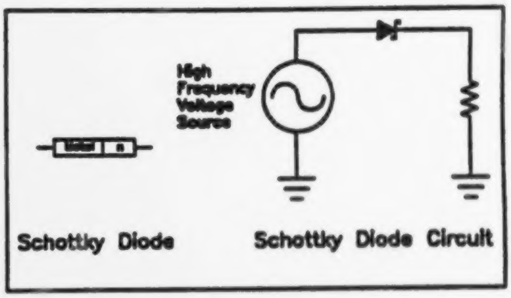
Voltage Tripler

Figure 3


A.C. Out
Voltage Source
D_1
D_2
D_3

Transient Suppressor

Figure 4


High Frequency Voltage Source

Schottky Diode

Schottky Diode Circuit

Figure 5

with an insulated coating around each granule. The higher voltage will break through the insulation and develop a path through the device. The lower voltages see the device as an open. The transient suppressor shown in figure 4 uses two zener diodes enclosed in one package that resembles an ordinary diode.

Each of the two diodes in the package will turn on at 184 V. Figure 4 shows D_1 and D_2 to illustrate how they work. The peak value of the 115 V rms voltage that supplies a power supply is 163 V. A voltage surge or spike that increases above *163 V to 184 V will turn on the zener diodes* and be shorted to ground. If the surge is positive, there is a 0.7 V drop across D_1, and then D_2 will short everything above 184 V to ground. The two diodes are placed back to back to allow the suppressor to work with both positive and negative voltage spikes.

SCHOTTKY DIODE

It takes a small amount of time for the electrons to move through the depletion area in an ordinary diode. This time is generally around 1 µs. This means that for 1 µs there will be electrons that have left the N-type material and have not dropped into a positive hole in the P-type material. The number of electrons will depend on the amount of current flowing in the diode when it was switched. This quantity of electrons in the depletion area is called *charge storage*. When the bias across the diode is switched, these electrons in the depletion area will move back, resulting in current flow.

At frequencies below 100 MHz, this is not a problem with the ordinary diode. As the frequency climbs up above 100 MHz, the delay in switching, caused by the movement of the electrons in the depletion area, starts to be a problem. In an ordinary diode, the electrons will travel from the N-type material across the depletion area and drop into a hole on the P-type material side. When the polarity switches, the electrons that are traveling will turn around and continue traveling back to their starting point. Although this is only a short distance, it does represent a considerable amount of current. The current flow is only for a short period of time; however, this short period of time becomes significant as the frequency climbs above 100 MHz.

The solution to this problem is the Schottky diode. Figure 5 shows such a diode, as well as how it is made. An ordinary diode will have P-type material fused to N-type material. The Schottky diode has N-type material fused to metal. The metal may be gold, silver, or platinum. Using metal instead of the P-type material results in no positive ions or holes. The electrons, moving from the N-type material, will go into larger orbits in the metal side of the diode. This difference in orbit size gives the diode action with no storage charge. When the diode is reverse-biased, there are no free electrons to travel back and give the diode a reverse current. The Schottky diode is used in computer circuits to increase the speed of the circuit. Designers of computer circuits are always looking for something that will give them more speed. The Schottky diode has only a 0.25 V drop across it. This makes it useful for rectifying low-voltage signals.

R. F. PROBE

The digital multimeter will measure dc and ac at low audio frequencies. If you need to measure high-frequency ac, then you will need either special equipment or a probe that will convert the ac to dc for your multimeter. There are some very good and generally expensive R.F. probes that can be used with your multimeter. There are also many very good complete meters for testing R.F. (radio frequency).

Notice, in figure 6, that we have a half-wave rectifier circuit between the probe and the meter. The sine wave coming into the probe is rectified and filtered to give the peak voltage as dc on the output. Remember that this dc will be 0.7 V below the actual peak voltage as a result of the voltage drop across the diode. This circuit will give a positive dc voltage. If we turned the diode around, the dc voltage would be negative. There are probes available that you can purchase with this circuit in them.

If you have a capacitor, preferably a 0.01 μF, and an ordinary diode, you can make up a probe when you need it. A probe that is quickly built out of spare parts in this manner may give you problems with strong radio signals. The R.F. may cause the meter to give erratic readings. You can turn the diode around and confirm your readings, if the same value shows up with a negative sign in front of it. To keep from loading the circuit under test, you should add a resistor in series with the diode going to the test point. If there is dc on the circuit that you are testing, then add a capacitor in series with the diode to block the dc. Some commercial radios will have this circuit built into the radio. To read the R.F. level in the radio, simply connect your meter to the appropriate points on the circuit.

VARICAP

Remember, when you studied basic diode theory, you learned that the depletion area will increase with increases in the voltage across the diode if it is reverse-biased. As the voltage changes across the diode, the size of the depletion area will change. A capacitor has two plates separated by a dielectric or insulator. If we look at the depletion area as the dielectric and the edge of the N-type and P-type material as the plates, we have a capacitor that will change the size of its dielectric with changes in voltage across it.

Figure 7 shows a diode that has been manufactured to *enhance its capacitance*. This kind of diode is called a varicap diode. Remember that all diodes have the same characteristics. A varicap diode is simply a diode that has been made to enhance this particular characteristic. Figure 7 shows the diode in a tuned tank circuit. When the diode is used in a circuit like this, it can be used to control the receiver frequency of FM radio and also modulate an FM radio. When it is used to control the receiver frequency, the circuit is called an AFC circuit, which stands for automatic frequency control.

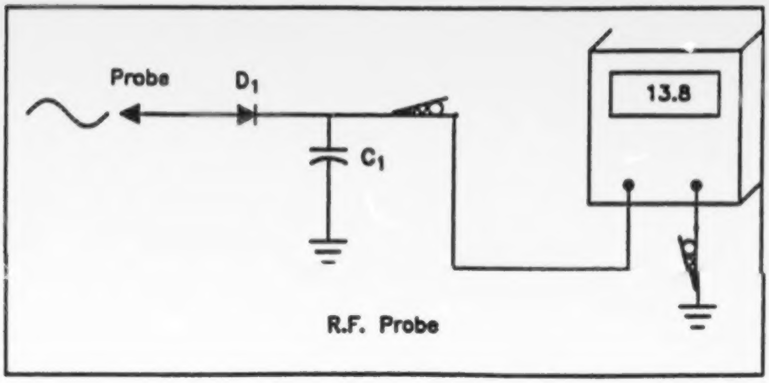

Probe
D1
C1
13.8
R.F. Probe

Figure 6

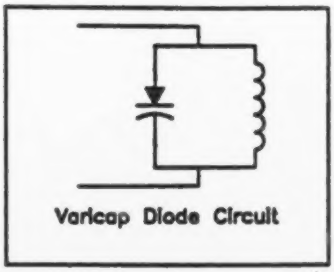

Varicap Diode Circuit

Figure 7

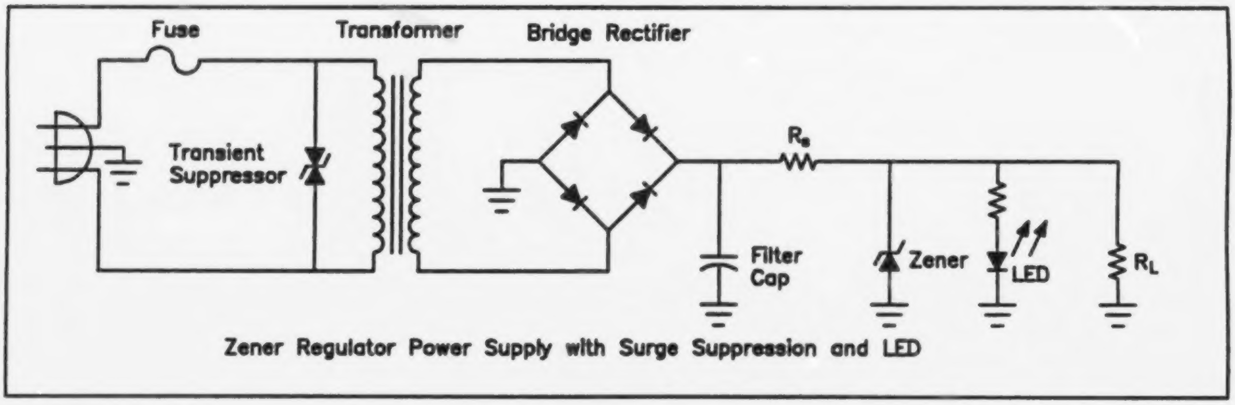

Fuse
Transformer
Bridge Rectifier
Transient Suppressor
Rs
Filter Cap
Zener
LED
RL
Zener Regulator Power Supply with Surge Suppression and LED

Figure 8

IMPROVING THE POWER SUPPLY

The power supply shown in figure 8 includes two additional components described earlier: (1) the transient suppressor in the primary of the transformer and (2) the LED on the output of the power supply circuit. If a momentary voltage surge should come into the primary circuit of this power supply, the transient suppressor would short it across the input. The higher level of current that would result would probably blow the fuse and protect the circuitry, including the transient suppressor, from prolonged exposure to higher levels of current.

The LED on the output of the circuit will add an additional 15 mA of current that must be figured when you are calculating the value of the series resistor R_S. Also, the value of the resistor in series with the LED is calculated by subtracting the 2 V drop across the LED from the supply voltage and dividing this voltage by the 15 mA needed for the LED. Pick a resistor as close to this as possible from your list of 5% resistors.

Students who are new to the study of electronics often become confused about the load that is shown in the schematics. Remember that nobody is going to go to the trouble of building a power supply to just heat up a resistor. The resistor symbol that is used for the load is a symbol of the load. The load can actually be another piece of equipment, a radio, or test equipment. The amount of current and the voltage requirements of this load can be used to determine the value of the resistor, which is shown in place of this load. The load is not part of the power supply circuit; it is the reason for the power supply circuit.

EXERCISE: Read each question carefully, and take your time. Use your notebook paper or scrap paper to solve the problems. Round off your answer to the three most significant digits.

1. What size resistor should you have in series with an LED in a 9 V circuit?
   A. 270 Ω
   B. 360 Ω
   C. 470 Ω
   D. 560 Ω
   E. None of the above

2. What value will the dc voltage be on the output of a doubler, if the input is 8 V rms?
   A. 16 V
   B. 19 V
   C. 23 V
   D. 27 V
   E. None of the above

3. If each segment in an LED display used 8 mA of current, how much total current would the display use for the number 2?
   A. 16 mA

B. 32 mA
C. 40 mA
D. 56 mA
E. None of the above

4. A sine wave with a 3 V peak value is fed into a half-wave rectifier using a Schottky diode. What is the output dc voltage?
A. 3 V
B. 2.75 V
C. 1.3 V
D. 0.7 V
E. None of the above

5. A varicap diode is across a tank circuit with 10 V dc on the diode. The resonant frequency of the tank circuit is 150 MHz. When the dc voltage is increased by 6 V to 16 V dc, the frequency changes 3 MHz. What would be the new resonant frequency if the dc voltage is reduced by 6 V to 4 V?
A. 13 MHz
B. 10 MHz
C. 7 MHz
D. 3 MHz
E. None of the above

6. What value should the resistance be, in series with an LED, if the LED circuit is in the primary of a transformer used in a power supply?
A. 33 kΩ
B. 7.5 kΩ
C. 1.2 kΩ
D. 470 Ω
E. None of the above

B-5

Transistor Theory

UNIT OBJECTIVE: Upon completion of this instructional unit, the student will be able to demonstrate a knowledge of how semiconductor devices operate and how they are used in a circuit.

SPECIFIC OBJECTIVES: Upon completion of this assignment, the student(s) will be able to demonstrate a knowledge of:

- how a transistor works
- how to test a transistor

TERMS

Alpha: Alpha is the mathematical ratio of collector current to emitter current in a transistor.

Beta: The beta is used more often then the alpha. It is the ratio of the collector current to the base current.

Before the development of the transistor in 1951, all electronic equipment used vacuum tubes. The vacuum tubes used a lot of power to heat the filament and were bulky. They also generated a lot of heat that had to be removed. The transistor was a major improvement for the electronics industry.

TRANSISTOR BASICS

A diode is made from two doped sections fused together. A transistor has three doped sections fused together. A transistor can have N-type, P-type, and N-type fused together (NPN) or P-type, N-type, and P-type (PNP). The areas where the different types of material are fused become depletion areas, just like in diodes. NPN and PNP transistors operate the same way—the only difference between them is the polarity. Since the polarity of supply voltages is usually positive to the circuit and a negative ground, the NPN transistor is usually easier to use in the circuit. This makes the NPN transistor the more popular transistor of the two.

Remember that with diodes, the N-type material received impurities to add extra electrons to the silicon. The P-type material received impurities to add extra holes. The manufacture of transistors has added another variable—the amount of doping added to the silicon. Notice in figure 1 that there are three pieces of doped silicon fused together to make the transistor. The emitter of the transistor is the most heavily doped, the base is lightly doped, and the collector's doping is between the other two.

The emitter gets its name because its job is to emit electrons into the base region, and the collector part of the transistor collects the electrons. The base portion of the transistor is located between the emitter and the collector and controls the flow of electrons. The base portion of the transistor is very thin. To understand the transistor, we must examine it at the atomic level.

Figure 2 shows two voltage sources to bias the transistor. This biasing will set up the transistor for normal operation. Notice that electrons are fed into the emitter, which is N-type material. The electrons are able to travel easily from one atom to another in the N-type material. When the electrons reach the junction between the emitter and the base, they meet the same kind of depletion area that exists in a diode. The base is very thin and there are two depletion areas, one for the base emitter junction and one for the base collector junction. These junctions are often called diode junctions.

The number of electrons allowed to flow from the emitter to the collector is determined by the flow of electrons through the emitter base junction. No electron flow through the base will result in no flow of electrons from the emitter to the collector. Remember that the base is lightly doped. The NPN transistor base will then have only a few holes. When a path is made for the electrons to flow through the emitter base junction, some of the electrons fall into the few holes in the base and flow out. Most of the electrons, about 99 percent of them, are then able to flow on to the collector region. The emitter base junction, like the diode, requires 0.7 V to push the electrons through it. This results in a 0.7 V bias across the emitter base junction on any working transistor.

As the electrons move through the emitter, they are at a high energy level. The energy level of the base is a little higher than that of the emitter. Some of the electrons will drop into holes in the base and pass on out the base lead. The rest of the electrons will travel through the base and drop into the collector. The collector has the lowest energy level of the three. When the electrons drop into the collector, they have to give up energy. This energy is usually in the form of heat. The collector of the transistor is where the heat is generated and also where it has to be removed.

The heat sink tab on large transistors, which are designed to handle large currents, is connected to the collector. For most transistors, there is a direct electrical connection to the collector. This will often help you pick out the collector in large transistors. When a large transistor is mounted, the heat sink must be electrically isolated from the ground in the circuit. This is often done with a piece of mica or plastic between the transistor and the external heat sink. In addition, heat-conducting grease is usually added to improve the heat flow. ***You learned that heat flows from a warm object to an object that is less warm in your physics classes. This principle is used with heat sinks.***

The schematic symbol for an NPN transistor is shown in figure 3. The arrow pointing to the emitter leg of the transistor shows the polarity of the transistor. If the arrow were pointing the other way, the transistor would be a PNP. The current flow for conventional current is with the arrow, just like the diode. When you are drawing a transistor freehand, you do not have to include the circle around the transistor. Your drawings will generally be neater without the circle. Most published schematics include the circle, but for freehand drawings it is usually better to omit it.

TRANSISTOR PARAMETERS

When the parameters of a transistor are listed, they will often show a voltage on a leg of the transistor referenced to another leg or to the circuit ground. For example, the breakdown voltage measured from the collector to the emitter would be labeled V_{CEO}. The subscript *CEO* stands for collector, emitter, and open base. This means the voltage measured at the collector and referenced to the emitter with the base lead open. When you see voltages listed this way, they are normally the maximum voltages for the transistor or the breakdown voltages. If the voltage is listed as V_C, it means the voltage at the collector and referenced to the circuit ground. If you connected the negative lead of your meter to the circuit ground and the positive lead of the meter to the collector of the transistor, you would be measuring the V_C. The capital letters indicate that the voltage or current is dc. Small or lowercase letters indicate the parameter is ac. Remember that there are three legs to a transistor. When you see a voltage or current listing two legs with the letter O, then the third leg is not connected to anything, or is open.

The maximum or breakdown voltages for many of the small signal transistors are from 30 to approximately 200 for the collector emitter junction. This voltage would be listed as the V_{CEO}. This voltage is normally reverse-biased in a working transistor, and it is the maximum working voltage for the circuit. The VBEO is usually 0.7 V and is forward-biased.

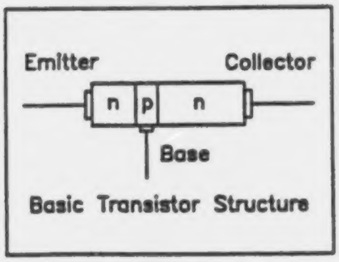
Two important ratios are used in discussing transistors—the *alpha* and the *beta*. The alpha is the ratio of the collector current to the emitter current. The beta is the ratio of the collector current to the base current.

$$\alpha = \frac{I_C}{I_E}$$ *formula for alpha*

$$\beta = \frac{I_C}{I_B}$$ *formula for beta*

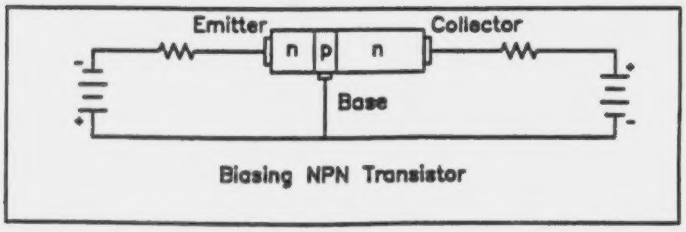
Look at figure 2 again, and notice that both the base current and the collector current pass through the emitter. The amount of base current is small compared to the collector current, which results in alpha being close to but not equal to 1. The beta, or ratio of the collector current to the base current, in many of the small signal transistors is from 75 to over 200. The beta is also considered to be the current gain of a transistor. The base current controls the amount of collector current. The beta is more commonly used in dealing with transistors. We will use the beta figures in our calculations as we study how to use transistors in circuits.

Figure 4 shows the transistor in a circuit. We have locked in the base current with a constant current generator. Remember that the constant current generator is a theoretical concept, and there is no component we can use that will give an ideal constant current generator. We will use this circuit to develop the graph in figure 5. Figure 5 shows the voltage across the transistor (or V_{CE}) graphed along the horizontal, and the current through the transistor graphed on the vertical. Starting with the first curve, which is the bottom curve, you will notice that it crosses the graph at the 0.5 mA current level. The constant current generator is feeding 5 μA into the base. Starting at the bottom left-hand corner of the graph where the zero volts and zero current start, we begin to


Emitter
Collector
n
p
n
Base

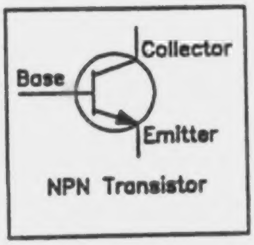
Basic Transistor Structure

Figure 1


Emitter
Collector
n
p
n
Base
-
+
+
-

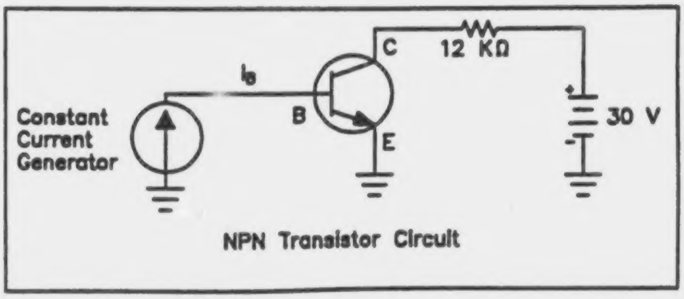
Biasing NPN Transistor

Figure 2


Collector
Base
Emitter

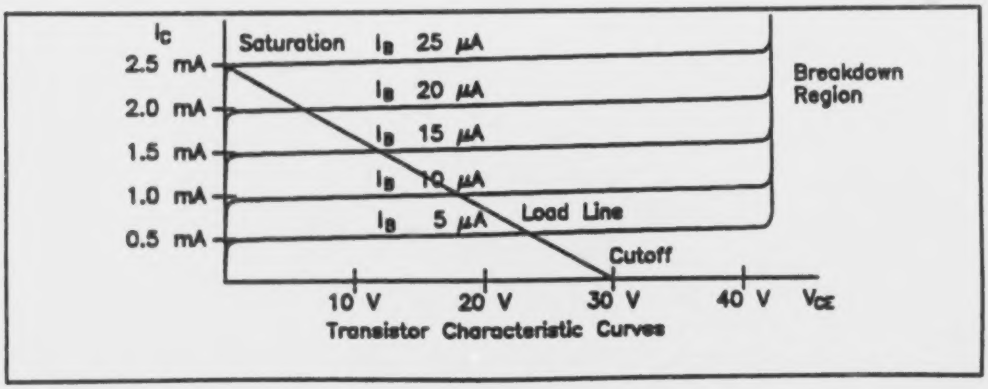
NPN Transistor

Figure 3


Constant Current Generator
I_B
B
C
E
12 KΩ
30 V
+
-

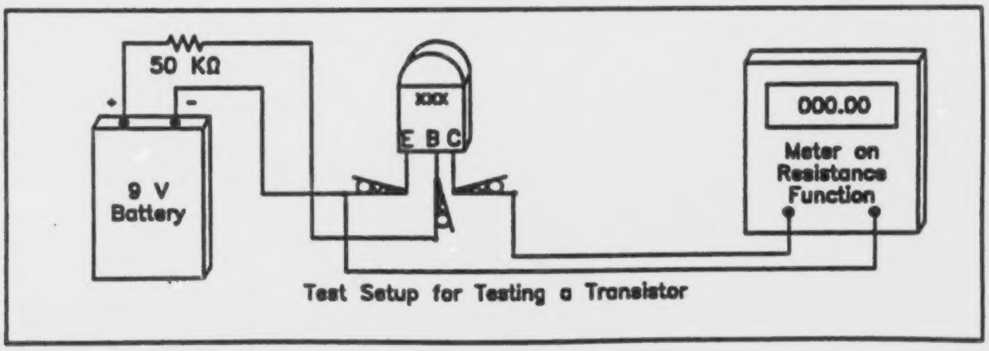
NPN Transistor Circuit

Figure 4



Transistor Characteristic Curves

Figure 5


50 KΩ
+
-
9 V Battery
xxx
E B C
000.00
Meter on Resistance Function

Test Setup for Testing a Transistor

Figure 6

increase the voltage across the transistor. The current starts climbing as the voltage across the transistor is increased. We would normally expect the current to increase with increases in voltage. Now, when the current reaches the 0.5 mA area, it starts to level off. We are still increasing the voltage, but the current is holding steady at approximately 0.5 mA. This is called the linear portion of the characteristic curve for a transistor. There will be a slight increase in current as the voltage is increased.

When the voltage goes past the breakdown point, the transistor starts conducting heavily, and the current goes high as shown in the breakdown region on the graph. The curve above this one goes through the same process. The difference is the higher current in the base. Notice how the amount of base current will determine the amount of collector current in the linear portion of the curve. This relationship between base current and collector current is the beta of this transistor. If you divide the collector current by the base current for this transistor, on any of the curves, you will get a beta of 100.

The line from the 2.5 mA point to the 30 V point is called the *load line*. This line represents the transistor circuit. The characteristic curves just covered represent the specific transistor. We can pick any voltage across the transistor and use the load line to determine the current through the transistor in the circuit that we used to find the load line. The exact point where the transistor is operating is called the Q point.

To calculate the position of a load line, find the two ends of the load line or the two extremes. Look at figure 4, and notice that if we open the transistor and measure the voltage across it or V_{CE}, we will have the end of the load line on the horizontal. The voltage end of the load line is the voltage across the transistor when there is no current flow through the transistor. The other end of the load line is the current through the transistor when there is no voltage drop across it. You would have no voltage drop across the transistor when the resistance in the transistor is zero ohms. Zero ohms resistance is a short. Examine figure 4 again, and notice what the current will be with the transistor shorted. The current is the voltage source divided by the series resistance. For the circuit in figure 4, the end of the load line on the horizontal is 30 V, and the current is the 30 V divided by 12 kΩ, or 2.5 mA. The point of maximum voltage and no current is called the *cutoff point*. The other end of the load line is called *saturation*.

TRANSISTOR TESTING

A circuit with transistors, resistors, and capacitors will usually develop problems in the transistors first. Resistors do not usually create problems, and capacitors are more rugged than transistors. If the transistor is handling large amounts of current, it is even more prone to fail before the other components of the circuit.

A transistor that is operating in a linear circuit should have approximately 0.7 V measured from the base lead to the emitter lead. If the base emitter junction does not have the 0.7 V, then either the base emitter junction or the collector base junction may have failed, or there may be a problem with the voltages that are fed to the transistor. This test is the quickest and easiest method to determine if the transistor has failed or is part of the failure in a circuit. Changes in the beta or frequency response of the transistor will not be caught by this measurement, but these problems are rare. This test is not foolproof. A problem in biasing the transistor can change the base emitter voltage. The transistor will have stopped working but may not have failed.

When troubleshooting a transistor circuit, test for the 0.7 V base emitter bias; if that is incorrect, check the voltages to ground on the other legs of the transistor. It is easy to measure voltages compared to changing transistors. Check all the voltages around the transistor before you commit to changing any components.

The best way to test transistors out of the circuit is with a curve tracer. This device will display curves on a video screen like the curves in figure 5. You will be able to determine the beta and polarity of the transistor easily with a curve tracer. Curve tracers are not always available when you need them. Some digital multimeters have a function that allows them to test diodes and transistors. This check will usually only tell you if the transistor is working and possibly the polarity. If none of this is available, then you can use the voltage function on your meter and a voltage source to test a transistor, as shown in figure 6.

To determine if a transistor is working, you need to bias the base of the transistor on and check to see if there is current flow through the collector emitter junctions. Any system that will turn on the transistor so you can check for the resistance across the collector emitter will work. If your meter does not have a diode checker function, it will not have the 0.7 V bias voltage to turn on the base emitter junction of a transistor. We have used a 9 V battery with sufficient resistance to keep from destroying the base emitter junction to turn on the transistor. Then the meter across the collector emitter path will tell us if the transistor turns on. A more complete check of the transistor would involve measuring the current in the collector emitter circuit and comparing it with the current in the base circuit. The ratio of collector current to base current is the beta of the transistor.

If you are trying to test a totally unknown transistor, then two voltage sources would be helpful (fig. 7). Use your voltmeter to check the current, and use the trial-and-error method until you get some readings that make sense. Be sure to limit the current from both supplies to avoid damaging the base emitter junction.

EXERCISE: Read each question carefully, and take your time. Use your notebook paper or scrap paper to solve the problems. Round off your answer to the three most significant digits.

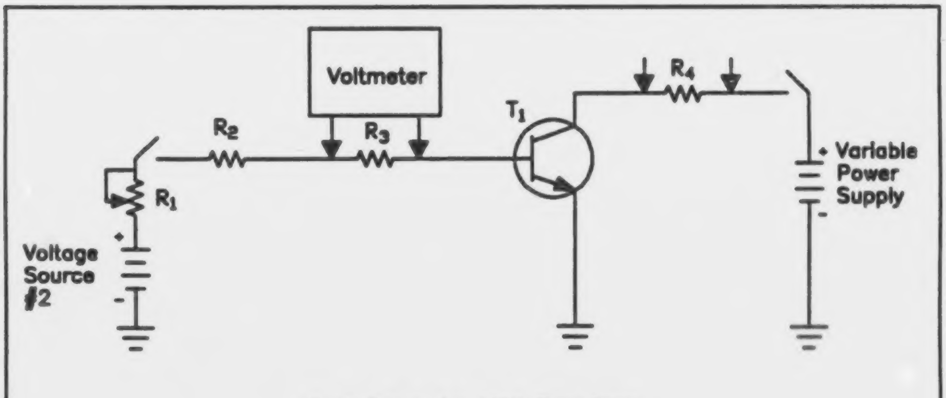
1. When a transistor is operating in a linear circuit, what is the voltage drop across the base emitter junction?
   A. 0.3 V
   B. 0.5 V
   C. 0.7 V
   D. 0.9 V
   E. None of the above

2. If the base current of a transistor is 12 µA and the beta is 135, what is the collector current?
   - A. 0.29 mA
   - B. 0.83 mA
   - C. 1.24 mA
   - D. 1.62 mA
   - E. None of the above

3. What is the beta of a transistor with 2.3 mA of collector current and 20 µA of base current?
   - A. 115
   - B. 135
   - C. 155
   - D. 175
   - E. None of the above

4. What would be the cutoff voltage for a transistor circuit with 15 V supply and a 1.2 kΩ resistor feeding the collector?
   - A. 15 V
   - B. 13 V
   - C. 11 V
   - D. 9 V
   - E. None of the above

5. What would the saturation current be for problem 4?
   - A. 35 mA
   - B. 18.7 mA
   - C. 12.5 mA
   - D. 8.34 mA
   - E. None of the above


Voltmeter
R$_4$
T$_1$
R$_2$
R$_3$
R$_1$
+
Variable
Power
Supply
-
+
Voltage
Source
#2
-

Test Setup for NPN Transistor

Figure 7

B-6

Transistor Switch

UNIT OBJECTIVE: Upon completion of this instructional unit, the student will be able to demonstrate a knowledge of how semiconductor devices operate and how they are used in a circuit.

SPECIFIC OBJECTIVES: Upon completion of this assignment, the student(s) will be able to demonstrate a knowledge of:

- how transistor switching works
- how to design a simple transistor switch

TERMS

Inductive load: An inductive load is a coil used for a load. The induced voltage from sudden switching can damage transistors and other solid-state devices.

Current source: An ideal current source will have a constant level of current output. A real current source can be shown as an ideal current source with a resistance across its output.

SIMPLE SWITCH

A common application of transistors is to take a weak signal input and use this signal to switch a load that requires a large amount of current. Sometimes the transistor switch is called a buffer since it buffers the load from the weak signal that causes the switch to operate. Figure 1 shows a basic transistor switching circuit. The switching signal is fed into the transistor through resistor R_B. The load that is switched on and off is resistor R_C.

You will use information learned in algebra classes to properly understand how this works. Notice that we have used V_{CC} for the voltage supply feeding the collector of the transistor. This term is used for a voltage supply that supplies a transistor circuit and feeds into the collectors of the transistors. If we had used the term V_{EE}, it would indicate that the supply was feeding into the emitter of the transistor. When we use these terms, it is understood that the voltage source is positive, unless we label it negative. The other side of the voltage supply is connected to the circuit ground. A different type of transistor called a JFET has a drain instead of a collector. The voltage source that feeds the drain on a JFET is called V_{DD}.

If we make R_C a 1 kΩ resistor and V_{CC} equal to 12 V, then we can examine how the circuit works. The resistance R_C is the load for the circuit. The load is the circuit or component that is being switched when the signal input to the base changes value.

If we assume that the signal driving the base switches from 0 to 5 V, then we have the information we need to calculate the value of R_B. The value of R_B must be high enough to limit the current to avoid damaging the base emitter junction. R_B must also be low enough to guarantee that the transistor will turn on completely. The beta of a transistor is the current ratio between the base and collector currents and will vary between transistors. For our calculations we will assume a beta of 100.

When the transistor is turned on completely, the collector current will be approximately V_{CC} divided by R_C. This will give 12 mA of collector current. To turn on the transistor completely, the base would need 1/100 of the 12 mA collector current. With 5 V feeding into the base circuit and the 0.7 V drop across the base emitter junction, we have 4.3 V across the resistor R_B. The 4.3 V divided by the 120 μA (12 mA/100) gives a resistor value of 35.8 kΩ. This resistor will be too high in value if the beta is less than 100, and we cannot be sure of the beta of the transistor. For a small signal transistor, we can safely assume that the beta will not go below 10. Using 10 as the beta for calculating the resistance of R_B gives a resistance for R_B that will protect the transistor from excessive current and allow enough current to turn on any transistor that we might put in the circuit.

A beta of 10 for a transistor means the base current is one-tenth of the collector current. We can calculate the base current as 1.2 mA which, when divided by the 4.3 V drop across R_B, gives 3.85 kΩ. This 3.85 kΩ resistance will work well with 5 V to the base and the 12 mA requirement for collector current. So long as the collector current does not increase, the V_{CC} voltage will have no effect on the operation of the circuit.

ADDING A RELAY

Notice the relay for a load in figure 2. A relay is a common device that is used to switch other loads and isolate the load from the switching circuitry. You would use a relay to switch electric motors or lights that demanded a lot of current from a 5 V switching circuit. The relay has a coil which will generate a strong induced voltage when the current changes suddenly. The induced voltage can be strong enough to destroy the transistor. The diode shown in parallel with the coil and reverse-biased in the circuit is used to short out the induced voltage. Always remember to include a diode, and in some cases a capacitor, in a circuit with a coil that can damage any solid-state circuits.

Let's give some values to the voltages in figure 2. The signal voltage, V_{in}, can be 5 V and V_{CC} can be 12 V. If the relay requires 100 mA of current to operate, then according to our rule of using a beta of 10, the base current would be 10 mA. The 5 V signal voltage minus the 0.7 V drop across the base emitter junction will leave 4.3 V across resistor R_B. This 4.3 V drop across the resistor divided by the 10 mA of base current that passes through the resistor will give us 430 Ω of resistance for resistor R_B. These values should result in a working circuit with any small signal transistor.

What size resistor would we need for R_B if the signal voltage V_{in} switched from 0 to 12 V? The value of resistor R_B depends on the input voltage V_{in}. We have already established a base current of 10 mA; therefore, the resistance becomes a function of the increased voltage drop across the resistor divided by the 10 mA. The increased voltage will be the 12 V minus the 0.7 V drop across the base emitter junction. This 11.3 V will then be divided by the 10 mA for a resistance of 1.13 kΩ. Notice that the value of the resistor is determined by the signal voltage. If the signal voltage is not stable, then the value of the resistance will need to be adjusted to cover the variation. Remember that too much current into the base emitter junction may damage the transistor, and not enough current can cause a low beta transistor to fail to switch.

CONTROLLING THE CURRENT

The circuit in figure 3 takes advantage of the base emitter junction voltage to lock in the load current. This circuit has some very interesting concepts, which you will see in some of the circuits in later assignments. The 0.7 V base emitter junction voltage will not change much between transistors or during the normal operation of the transistor. The voltage source, V_{BB}, in figure 3 is 0.7 V above the voltage at the emitter. This emitter voltage is the voltage across resistor R_E. If the voltage source V_{BB} is a stable voltage, then the voltage across R_E will be stable as well. A stable voltage across R_E will result in a stable current flow through the emitter. The collector current is approximately equal to the emitter current. Remember that the beta is usually around one to three hundred, which will make the difference between the collector and the emitter current 1% or less. The only difference between the emitter current and the collector current is the small amount of base current. This gives this circuit the advantage of being able to lock in the collector current.

Let's give this circuit some values and look at it. We can make V_{BB}, the signal voltage, equal to 5 V. If R_C needs 5 mA of current, then we can determine the value of R_E. The 5 V from V_{BB} minus the 0.7 V which is across the base emitter junction will leave 4.3 V across the resistor R_E. This 4.3 V divided by the 5 mA we need for R_C will give a resistance value of 860 Ω. Notice that we did not need to know anything about beta to lock in the current through R_C. This circuit will work well with LEDs and other devices that operate more effectively with a constant current.

If the input signal voltage is 12 V and the load R_C is an LED that required 15 mA, what should the resistance value be for R_E? The 12 V minus the 0.7 V base emitter junction voltage will leave 11.3 V across the emitter resistor. This 11.3 V divided by the required 15 mA of current gives a resistor value of 753 Ω.

MORE COMPLEX SWITCHING CIRCUITS

Notice the diode D_1 and the capacitor C_1 in the circuit in figure 4. We can examine the circuit by starting with a discharged capacitor and zero volts on the input. When the signal input goes high or switches to its on voltage, the diode will pass current on to the capacitor and the base of the second transistor T_2. The current fed into the base of T_2 will turn on this transistor and hold the current through the LED constant. When the signal input goes to zero V, the current will no longer pass through the diode. The charged capacitor C_1, will supply current to the base of transistor T_2. The diode will block the current from going back down R_1 to ground. The capacitor will keep the LED turned on for a short time after the signal goes to zero.

This circuit using the capacitor and the diode is often used for a simple time delay. The current does not remain constant through the LED when the signal drops to zero. Notice that as

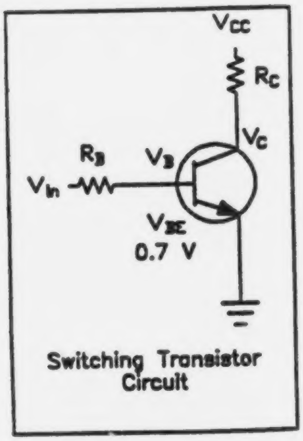

Vcc
Rc
Vc
RB
VB
Vin
VBE
0.7 V
Switching Transistor Circuit

Figure 1

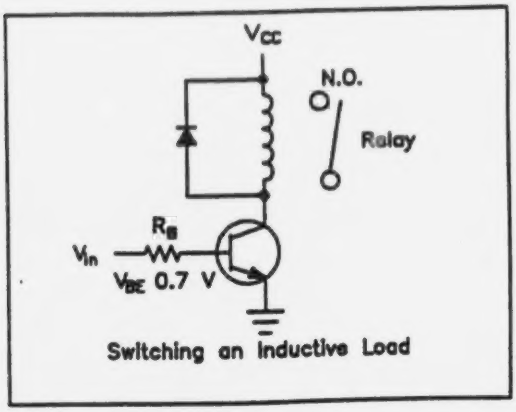

Vcc
N.O.
Relay
RB
Vin
VBE 0.7 V
Switching an Inductive Load

Figure 2

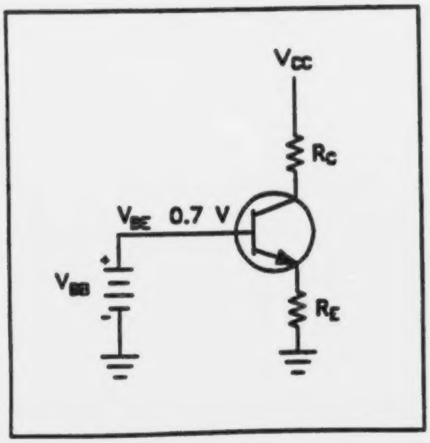

Vcc
Rc
VBE 0.7 V
VBB
+
-
RE

Figure 3

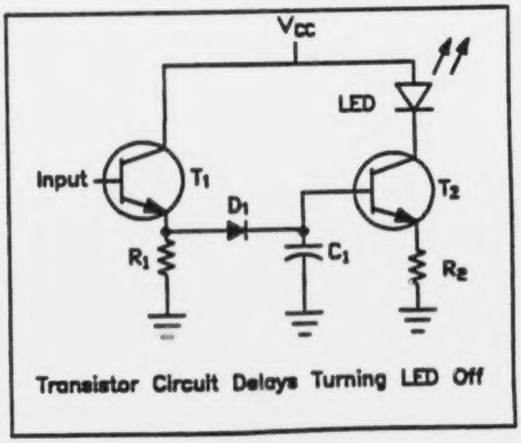

Vcc
LED
Input
T1
D1
T2
R1
C1
R2
Transistor Circuit Delays Turning LED Off

Figure 4

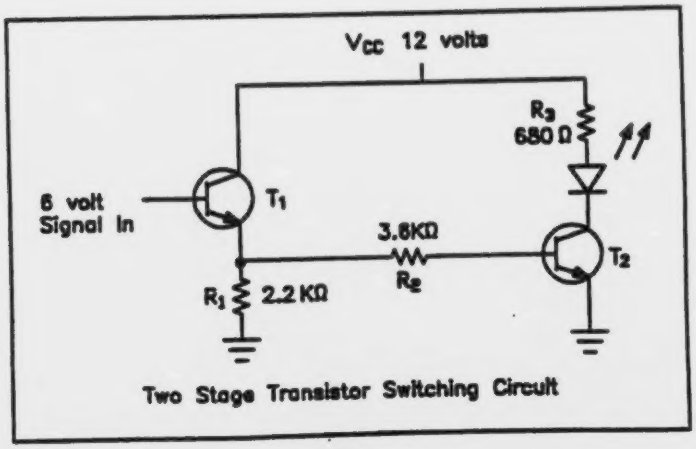

Vcc 12 volts
R3
680 Ω
6 volt
Signal In
T1
3.6KΩ
R2
T2
R1
2.2 KΩ
Two Stage Transistor Switching Circuit

Figure 5

the capacitor discharges, the voltage will drop and the voltage drop across the emitter resistor will drop, reducing the current through the LED.

If the input signal in figure 4 is 5 V, what should the values of the resistors be? Transistor T_1 is an emitter follower. An emitter follower has a low output impedance, or we can describe it as having much current available to the diode D_1. The emitter resistor for T_1 will not affect the current levels very much so we can just pick a 1 kΩ resistor for this spot. The value of the capacitor will depend on the amount of time delay that is required. Remember, the time constant is equal to the capacitance times the resistance. The resistance for our circuit is in the base emitter junction which is hard to measure and the emitter resistor R_2. When the 5 V is on the signal input, the voltage at the emitter of the first transistor T_1 is 4.3 V. This 4.3 V drops another 0.7 V when it passes the diode. The base of T_2 will see a maximum of 3.6 V. The base emitter junction of T_2 will drop this 3.6 V another 0.7 V to 2.9 V across the emitter resistor R_2. Remember that we need 15 mA to operate our LEDs. The 2.9 V divided by the 15 mA will give 193 Ω for our emitter resistor.

BASIC RULES FOR SWITCHING TRANSISTORS

When you see a resistor in series with the base of a transistor, you can assume that the transistor is used for switching and the resistor is needed to limit the current to the base of the transistor. If you are using small signal transistors in a switching circuit, the minimum beta figure to use is 10. Transistors designed for higher current levels may have a beta close to 10. You should check the manufacturers data sheet to determine the beta for any transistor in question. A switching circuit with more than one transistor can be used to invert the logic. The signal taken from the collector will always be inverted, or 180° out of phase with the signal on the base. When a signal is taken from the emitter, it is in phase, or the same logic as the signal on the base. If you do not have a resistor in the emitter of the transistor with an LED or other current-sensitive device in the collector, then you must limit the current through the device. Add a resistor in series with the LED to limit the current when necessary. Do not forget to add a diode to reduce the induced voltage from a relay when it is in a switching circuit.

EXERCISE: Read each question carefully, and take your time. Use your notebook paper or scrap paper to solve the problems. Round off your answer to the three most significant digits.

1. When the signal voltage is 6 V, what is the emitter voltage on T_1?
   A. 12 V
   B. 0.7 V
   C. 6.7 V
   D. 5.3 V
   E. None of the above

2. In figure 5, when the signal input voltage is at 0 V, what is the voltage on the collector, V_C, of T_2?
   A. 0 V
   B. 0.7 V
   C. 6 V
   D. 12 V
   E. None of the above

3. What is the voltage on the base of transistor T_2, with the signal on?
   A. 12 V
   B. 6.7 V
   C. 0.7 V
   D. 0 V
   E. None of the above

4. What changes would you make to the circuit in figure 5 if V_{CC} changed to 18 V?
   A. Change R_2 to a 4.2 kΩ resistor and R_3 to 1.2 kΩ.
   B. Change R_3 to a 1 kΩ.
   C. Change R_1 to a 3.6 kΩ and R_2 to a 4.2 kΩ.
   D. No changes are needed.
   E. None of the above

5. Assume that the circuit in figure 5 has failed. You find that there is 0 V on the collector of T_2 and 0.7 V on the base of T_2. What is the problem?
   A. Transistor T_2 has failed open.
   B. The LED is open.
   C. Resistor R_2 has shorted.
   D. Transistor T_1 has failed open.
   E. None of the above

6. If transistor T_1 has a beta of 100, what is the base current into this transistor with the 6 V signal voltage on?
   A. 6 µA
   B. 12 µA
   C. 24 µA
   D. 48 µA
   E. None of the above

7. If the LED in figure 5 stays on continually, and you find that the voltage on the emitter of T_1 remains at 12 V with or without the signal voltage, what has failed?

   A. Transistor T_2 has shorted to ground.
   B. Resistor R_3 has shorted.
   C. Transistor T_1 has failed open.
   D. Transistor T_1 has failed shorted.
   E. None of the above

8. You find that the LED does not light when the signal voltage is on and the collector of T_2 has 12 V on it. What has failed?

   A. The LED is open.
   B. Transistor T_1 is open.
   C. Transistor T_2 is open.
   D. Resistor R_3 is shorted.
   E. None of the above

B-7

Transistor Bias

UNIT OBJECTIVE: Upon completion of this instructional unit, the student will be able to demonstrate a knowledge of how semiconductor devices operate and how they are used in a circuit.

SPECIFIC OBJECTIVES: Upon completion of this assignment, the student(s) will be able to demonstrate a knowledge of:

- how to bias a transistor circuit
- how to design simple linear transistor circuits

TERMS

Voltage divider bias: A common system of biasing a transistor to operate as an amplifier.

Complementary circuits: A circuit that has the opposite polarity of transistor such as NPN and PNP, and all its voltages and currents are opposite in polarity. The NPN transistor is the complement of a PNP transistor.

TRANSISTOR INPUT AND OUTPUT

An electronic technician will often be faced with the problem of connecting two pieces of equipment that are not compatible. The input of one piece of equipment may require a stronger signal than the output of the other piece of equipment can provide. A technician must be able to design and build simple circuits that can solve this type of problem. In this assignment, you will learn one method of designing simple transistor circuits. This method will not provide the best possible circuit, but it will quickly provide one that will work. You will need advanced study at the university level to learn how to design optimum circuits.

Figure 1 shows the schematic symbol for a transistor, with which you are already familiar, and the arrangement of P-type and N-type material, as well as an equivalent circuit for the transistor.

Remember how the Thevenin and Norton equivalent circuits helped you to understand how a complex circuit affected the circuitry to which it was connected. Figure 1 shows the equivalent circuit for the input of the transistor and a separate circuit for the output of the transistor. ***Your studies in algebra will help you understand this concept.*** Notice that the input equivalent circuit resembles a Thevenin equivalent circuit and the output resembles a Norton equivalent circuit.

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The input equivalent circuit is not intended to be a Thevenin equivalent circuit. The input circuit is what a source circuit sees when it is driving the transistor. The output circuit is the Norton equivalent circuit for the output of the transistor.

It is easier to understand how a transistor works by looking at only one part of it at a time. We can start by *examining the input circuitry.* A source circuit, such as another transistor, would see a small amount of resistance and the 0.7 V base emitter junction when driving the input of a transistor. The voltage source in figure 1 is the 0.7 V base emitter junction. A transistor has just a small amount of resistance in series with this. Because the resistance is small, we consider the input to a transistor to be controlled by current. Another way of saying this is to consider the input to have a low input impedance. The output circuitry of the transistor is a Norton equivalent circuit. This transistor output resembles a current source.

LINEAR TRANSISTOR CONTROL

A transistor will control the current from its output based on the amount of current fed into the base circuitry. The problem is to feed the right amount of current into the base. When a transistor is in an operating circuit with no signal input, it should have enough current coming into the base to provide a level of current from the output that would center it on the load line. Centering it on the load line means the current level should be halfway between saturation and cutoff. When the signal comes into the base, there will be room for the output to swing from saturation to cutoff if the signal is that strong. This will give the full current range of the transistor.

Remember, the ratio of collector current to base current is the beta of a transistor. This is also called the *current gain* of a transistor. A transistor's beta will change with temperature and is different between transistors of the same type. We need to eliminate the effect of beta in our circuit to have a stable circuit. An acceptable circuit must allow for changes in beta and still work.

In the early days, circuits were built using vacuum tubes. A vacuum tube is a voltage-controlled device, and the transistor is a current-controlled device. Some of the early attempts at biasing a transistor were attempts to copy the methods used to bias the tube, and they did not work well. The method that is most popular today evolved from methods that feed current to the base. The most common method of biasing the transistor, or establishing an amount of current to center the output, is the voltage divider system. This system in combination with a resistor in the emitter works very well.

VOLTAGE DIVIDER BIAS

Notice, in figure 2, how the resistors R_{B1} and R_{B2} form a voltage divider feeding the base of the transistor. To form a stable current source for the base, the voltage divider must have much more current flowing through the divider than the amount of current required by the base. If we assume a beta of 100, then the amount of current flowing through the base is 1/100 of the amount of current flowing through the collector. The voltage divider should have, as a bare minimum, at least 10 times more current than the base current.

The ten-step design process we have developed will give you 20 times more current. You can find all four resistors that are needed to bias a transistor by performing the operations shown in the

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10 Step Formulas

Step 1 $V_{CE} = \frac{V_{CC}}{2}$

Step 2 $R_C = \text{Load } Z$

Step 3 $R_E = \frac{R_C}{6}$

Step 4 $V_{R_E} = \frac{V_{CC} - V_{CE}}{7}$

Step 5 $V_B = V_{R_E} + 0.7$

Step 6 $I_{CQ} = \frac{V_{R_E}}{R_E}$

Step 7 $I_{BQ} = \frac{I_{CQ}}{\text{Beta}} = \frac{I_{CQ}}{100}$

Step 8 $I_{VD} = 20\ I_{BQ}$

Step 9 $R_{B2} = \frac{V_B}{I_{VD}}$

Step 10 $R_{B1} = \frac{V_{CC} - V_B}{I_{VD}}$

ten formulas. Before you start, you will need the value for V_{CC} and the load impedance Z. We can use the circuit in figure 2 as a guide when we go through the ten steps. Before we begin, we need to have a value for V_{CC} and for the load impedance. The load impedance can be 1.8 kΩ, and V_{CC} can be 12 V.

Starting with **Step 1** gives us V_{CE}, or the voltage across the transistor. This voltage is equal to 6 V. Notice that V_{CE} is equal to half of V_{CC}. This step helps to center the transistor's Q point in the middle of the load line.

Step 2 can be changed a little to improve individual circuits. The best place to start, as shown, is by making the value of the collector resistor equal to the load impedance. To reduce the amount of losses between circuits, sometimes you might want to increase the collector resistance. Since the load impedance was 1.8 kΩ, the collector resistance will be 1.8 kΩ.

In **Step 3**, we find the value of the emitter resistor. The emitter resistor, R_E, is equal to the collector resistance divided by 6. The 1.8 kΩ divided by 6 gives 300 Ω for the emitter resistance. Before you can build this circuit, you would need to convert the calculated resistance values to the standard 5% resistance values.

In **Step 4**, we find the voltage across the emitter resistor. The formula shows that we subtract the voltage drop across the transistor, or V_{CE}, from V_{CC}. Notice that Step 1 gave V_{CE} as half of V_{CC}. The voltage across the emitter is 0.86 V.

In **Step 5**, we will find the voltage at the base using the voltage calculated at the emitter. The base emitter junction voltage is 0.7 V, which when added to the emitter voltage will give the base voltage. The base voltage, V_B, is the 0.86 V plus the 0.7 V across the base emitter junction. This is a total of 1.56 V.

Step 6 will give the collector current, I_{CQ}. The letter Q after the C stands for the Q point, so this is the collector current at the Q point. The difference between the collector current and the emitter current is very small. With a beta of 100, the difference will be 1 percent. This is close enough to the emitter current that we usually consider them to be the same value. This collector current is the emitter voltage, V_{RE}, divided by the emitter resistance, R_E, or 2.87 mA.

In **Step 7**, the base current, I_{BQ}, is the 2.87 mA of collector current divided by beta. You will not usually know what the beta of a transistor is. For our calculations, we will use a beta of 100, which is a good compromise for these formulas. The 2.87 mA divided by 100 will give us 28.7 µA of base current.

In **Step 8**, we find the current through the resistive divider. This value is 20 times the base current, I_{BQ}, or 0.574 mA.

Step 9 will now give us the value of R_{B2}, or the lower resistor in the voltage divider. The voltage at the base divided by the current through the divider gives us this value, which is 2.7 kΩ.

Step 10 now gives us the upper resistor value, R_{B1}, which is 18.2 kΩ. We have now found values for the four resistors R_C, R_E, R_{B1}, and R_{B2}. We now have a design for a working circuit.

LOAD LINES

Figure 3 shows the characteristic curves and the load line for a transistor circuit like the one in figure 4. The cutoff point on our graph is equal to the voltage across the transistor, or V_{CE}, with

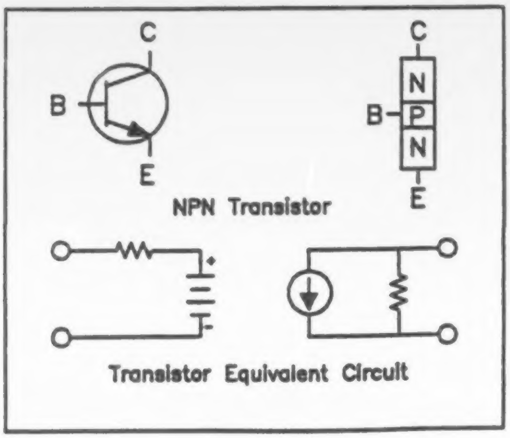
C
B
E
C
N
B
P
N
E
NPN Transistor
+
Transistor Equivalent Circuit

Figure 1

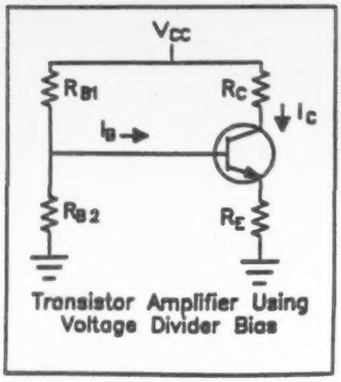
Vcc
RB1
Rc
Ic
IB
RB2
RE
Transistor Amplifier Using Voltage Divider Bias

Figure 2

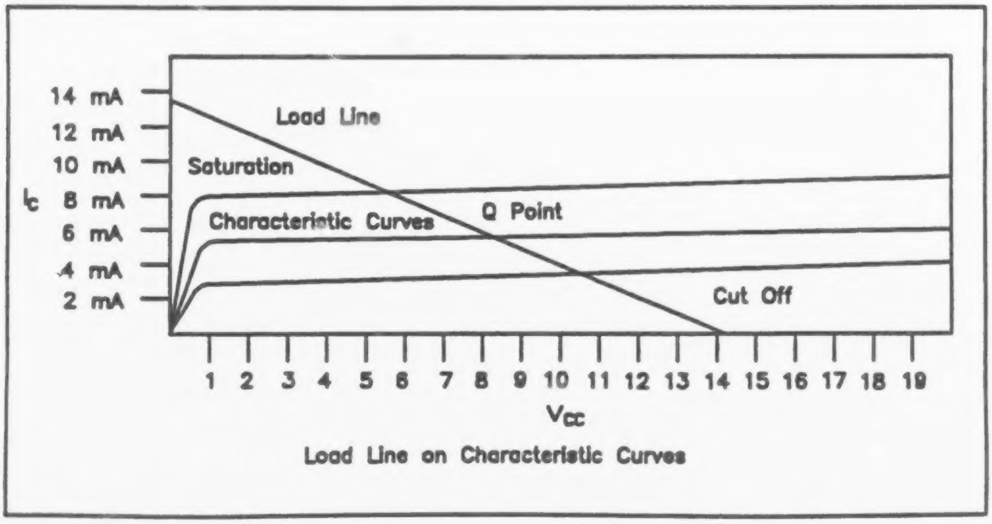

Figure 3

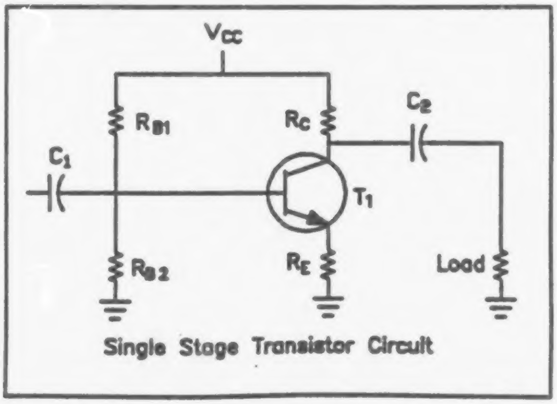
Vcc
RB1
Rc
C2
C1
T1
RB2
RE
Load
Single Stage Transistor Circuit

Figure 4

no current through the transistor. No current through the transistor will result in a voltage across the transistor of V_{CC}. This is the area where the transistor will be turned off, or cut off.

The saturation point is the point of maximum current or the amount of current through the transistor with no voltage drop. No voltage drop is V_{CE} equal to zero. You can find the saturation point by dividing V_{CC} by the sum of the collector and emitter resistance. The saturation point is where the transistor is turned on completely and cannot be turned on any harder. No additional current can flow.

When there is no signal into the transistor, the voltage across the transistor and the current through it are represented by the Q point. The Q point is considered the operating point of the transistor. The voltage across the transistor, or V_{CE}, can be used to quickly find the Q point. Notice that our design has put the Q point or operating point at 8 V, which is a little more than half of V_{CC}.

TWO OR MORE STAGES

Figure 5 shows two transistor stages connected together. There are other ways to design transistor circuits, and figure 5 was designed using another method. It is important for you to be able to calculate the voltages on a transistor circuit. Using the ten steps to help calculate these voltages will not work when the circuit was designed using another method.

The first step in analyzing a transistor circuit is to find the voltage at the base of the transistor on the stage where you begin. Notice that capacitors separate the stages. The capacitors will block the dc voltages from one stage from interfering with the other stage. We can start with the stage with transistor T_1 in it. Finding the voltage at the base of T_1 is simply the same as finding the voltage between the two resistors that make up the voltage divider. This is shown in formula 1. The voltage at V_B is the same as the voltage across the resistor R_{B2} and is equal to 1.97 V.

$$V_{RB2} = \frac{R_{B2}(V_{CC})}{R_{B1}+R_{B2}} \qquad \textit{formula 1}$$

The next step in analyzing this circuit is to find the emitter voltage, or V_E. V_E is 0.7 V less than V_B for an NPN transistor. A PNP transistor would be the opposite, or 0.7 V higher at the emitter. V_E is equal to 1.27 V. Now we can find the current through the emitter resistor. We have the voltage across it and the resistance value. Dividing the 1.27 V by the 680 Ω gives us 1.87 mA of emitter current.

The emitter current and collector current are so close that we consider them to be the same. We can find the voltage drop across R_C by multiplying the collector current by R_C. The voltage drop across the resistor R_C is 5 V. The 12 V for V_{CC} minus this 5 V will give the voltage at the collector, or V_C, which is 7 V. The voltages on the second stage can be found in the same manner. Capacitor C_2 will keep the dc voltages on the first stage from interfering with the second stage.

EXERCISE: Read each question carefully, and take your time. Use your notebook paper or scrap paper to solve the problems. Round off your answer to the three most significant digits.

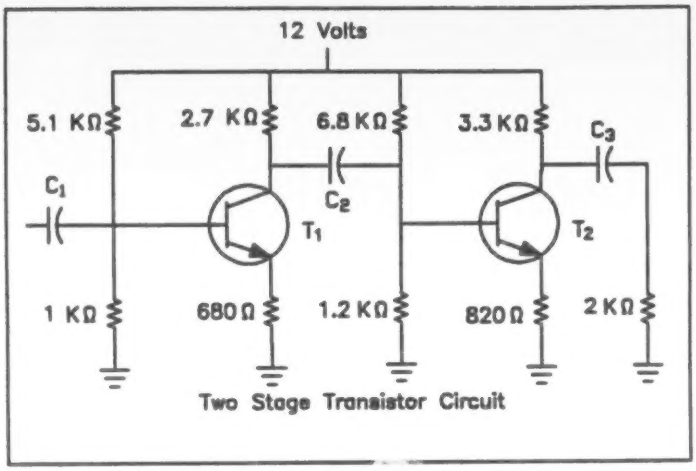
12 Volts
5.1 KΩ
2.7 KΩ
6.8 KΩ
3.3 KΩ
C3
C1
C2
T1
T2
1 KΩ
680 Ω
1.2 KΩ
820 Ω
2 KΩ
Two Stage Transistor Circuit

Figure 5

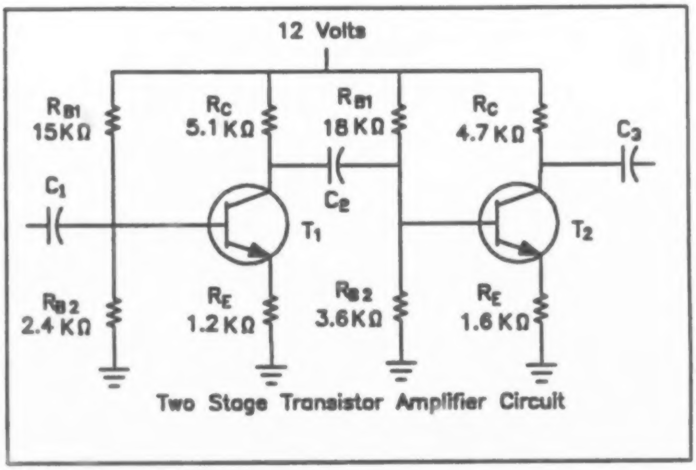
12 Volts
RB1
15KΩ
RC
5.1 KΩ
RB1
18 KΩ
RC
4.7 KΩ
C3
C1
C2
T1
T2
RB2
2.4 KΩ
RE
1.2 KΩ
RB2
3.6KΩ
RE
1.6 KΩ
Two Stage Transistor Amplifier Circuit

Figure 6

1. Calculate the following voltages for the circuit in figure 6.
   A. V_B for T_1 ______
   B. V_E for T_1 ______
   C. V_C for T_1 ______
   D. V_B for T_2 ______
   E. V_E for T_2 ______
   F. V_C for T_2 ______

2. If resistor R_E broke away from the emitter transistor T_1, what would be the following voltages?
   A. V_B for T_1 ______
   B. V_E for T_1 ______
   C. V_C for T_1 ______
   D. V_B for T_2 ______
   E. V_E for T_2 ______
   F. V_C for T_2 ______

3. If transistor T_2 had a short from the collector to the emitter, what would be the following voltages?
   A. V_B for T_1 ________
   B. V_E for T_1 ________
   C. V_C for T_1 ________
   D. V_B for T_2 ________
   E. V_E for T_2 ________
   F. V_C for T_2 ________

B-8

Transistor Amplifiers

UNIT OBJECTIVE: Upon completion of this instructional unit, the student will be able to demonstrate a knowledge of how semiconductor devices operate and how they are used in a circuit.

SPECIFIC OBJECTIVES: Upon completion of this assignment, the student(s) will be able to calculate:

- the voltage gain of a simple transistor circuit
- the impedance of a simple transistor circuit

TERMS

Swamping: The emitter resistor that is not bypassed with a capacitor is called swamping.
Small signal: A small signal input will result in less than 10 percent variation in collector current.
Linear: A linear amplifier will not change the shape of the signal input.

ANALYZING BASE BIAS IN TRANSISTOR CIRCUITS

In this assignment, we will be examining how the transistor operates in a linear circuit. A linear circuit does not change the shape of the signal. The switching circuits that you studied in a previous assignment are nonlinear circuits.

You have already learned how to design a transistor circuit that will be approximately centered between saturation and cutoff. The circuit in figure 1 shows a complete single-stage transistor circuit. Resistors R_{B1} and R_{B2} provide the base bias for transistor T_1, which centers the operating point, or Q point, between saturation and cutoff. These resistors provide a voltage divider that sets up an average level of current feeding into the base of the transistor. The signal comes from the Thevenin equivalent circuit shown feeding into coupling capacitor C_1.

If the input signal is a 1 kHz sine wave, the signal will change the input current that is feeding into the base at the 1 kHz rate. This will cause the base emitter junction current to vary. The collector current will then vary with the change in current coming into the base. The amount of change in collector current compared to the change in base current will depend on the beta of the transistor. A beta of 100 will result in 100 times more collector current than base current.

If the signal that is fed into the base of the transistor is strong enough, it will drive the transistor into saturation and cutoff. When you view this on an oscilloscope, you will see flat spots on either the top or the bottom or on both the top and bottom of the signal. ***Looking at an oscilloscope is like looking at the graphs you studied in your math courses.*** These flat spots introduce a lot of distortion to the signal.

The term *small signal* is used to describe a signal level that will not cause the transistor to go into saturation or cutoff. The small signal level should be small enough to operate the transistor over only a small portion of the full range that is available. A small signal is defined, according to industry standards, as an input signal that causes less than 10 percent variation in the collector current.

COUPLING AND BYPASS CAPACITORS

Capacitors C_1 and C_2, in figure 1, are coupling capacitors, coupling the signal in and out of the circuit. Capacitor C_3 is a bypass capacitor. The bypass capacitor bypasses the emitter resistor, allowing the signal to pass on to ground. A bypass capacitor used across the emitter, like C_3, puts the emitter of the transistor at ac ground. We normally assume that the capacitors in a circuit have negligible impedance to the signal. You should remember formula 1, for capacitive reactance, from your previous studies.

$$X_C = \frac{1}{2\pi fC}$$ *formula 1*

Notice that the capacitive reactance is inversely proportional to the frequency. This means that when the frequency goes up, the capacitive reactance will go down by a proportional amount. The industry standard states that the capacitive reactance of the coupling capacitor or bypass capacitor should be less than 10 percent of the series resistance feeding the capacitor to be considered an ac short for most calculations. In figure 1, the coupling capacitor C_1 should have an X_C that is 10 percent or less than the value of R_{TH} to be considered an ac short.

ELECTRONIC NOTATION

Voltages and current values will be shown in lowercase letters if they are ac values and in uppercase or capital letters if they are dc values. (Notice that we use lowercase for the terms *ac* and *dc*). The voltage across the collector emitter would be shown as v_{ce} for an ac voltage and V_{CE} for a dc voltage.

When we use two subscripts, the second subscript is the reference. A single subscript is referenced to the circuit ground. An exception to this rule is the voltage source in figure 1. The Thevenin equivalent voltage, V_{TH}, is an ac source. The subscript TH indicates Thevenin and is not a voltage from T to H.

The minus sign is also used to show an ac signal that is 180 degrees out of phase. These minus signs that show phase can create confusion in some formulas.

EQUIVALENT CIRCUITS

Figure 1 can be separated into its ac and dc equivalent circuits. We have done this in figure 2. To understand how the circuit responds to ac and dc, we have to remember that the capacitor is the component that makes the difference. The capacitor will block dc and pass ac. If the capacitive reactance is less than 10 percent of the series resistance, then we can consider the capacitor to be a short as far as ac is concerned.

The difference between the two circuits in figure 2 involves the capacitors. To make the dc equivalent circuit, we removed the capacitors. This equivalent circuit is what the dc portion of the circuit sees. Note that there is not a lot of difference between the dc equivalent circuit and the complete circuit except that the signal inputs and outputs are gone.

There are more changes to the ac equivalent circuit. Short-circuiting the capacitors allows us to move the components around as you see them in the schematic. The emitter resistor is gone since there was a capacitor in parallel with it which shorted it out.

You will also notice that R_{B1} and R_C both go to ground. The voltage source, V_{CC}, will appear to any ac signal as ground. When you studied power supplies, remember that you added capacitive filtering to reduce the ripple on the output. That ripple is ac just like the signal. A power supply will not be a good supply if it does not have a low output impedance. A low output impedance can be described as a short for ac to ground.

Notice how the signal coming from the Thevenin equivalent circuit will see the two voltage divider resistors in parallel. Also notice how the load and the collector resistor appear in parallel to the output signal. These parallel combinations will show up in some of the formulas that we are about to study.

CIRCUIT DESIGN

The only difference between figure 3 and figure 1 is that we have split the emitter resistor. Notice that we show a resistor r_E and R_E with the capacitor connected between them.

The ac signal coming into the case of the transistor will see three resistances in series through the base emitter path. The first resistance is the ac emitter resistance. This ac emitter resistance, r_e', is the internal resistance, inside the transistor in the emitter path. We can calculate this resistance using Ohm's law, which would be the ac voltage across the base emitter junction divided by the ac emitter current. The problem with this method for calculating the r_e' is the difficulty of obtaining these ac voltage and current figures. Formula 2 was developed to make it easier to find a value for r_e'.

$$r_e' = \frac{25}{I_{E\ (\text{in mA})}}$$ *formula 2*

Formula 2 tells us we can find the ac emitter resistance by dividing the emitter current (in mA) into 25. Note that you must use the emitter current as a whole number in its mA form. For example, a transistor stage with 1 mA of emitter current will have an ac emitter resistance of 25 Ω.

Now that we have the r_e', we can calculate the voltage gain of a transistor stage. The voltage gain can be defined as the ratio of the voltage out divided by the voltage in. Since the voltage drop

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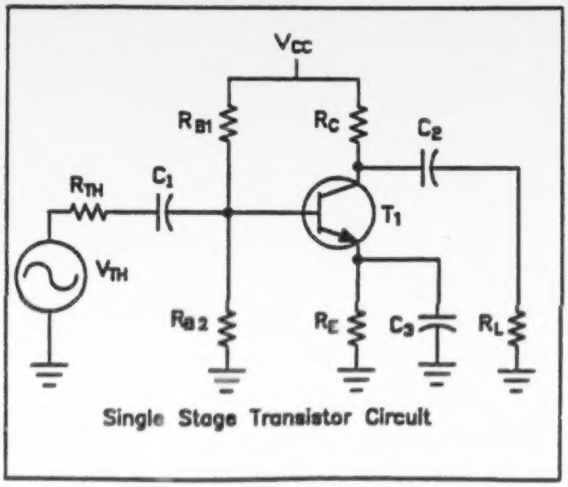
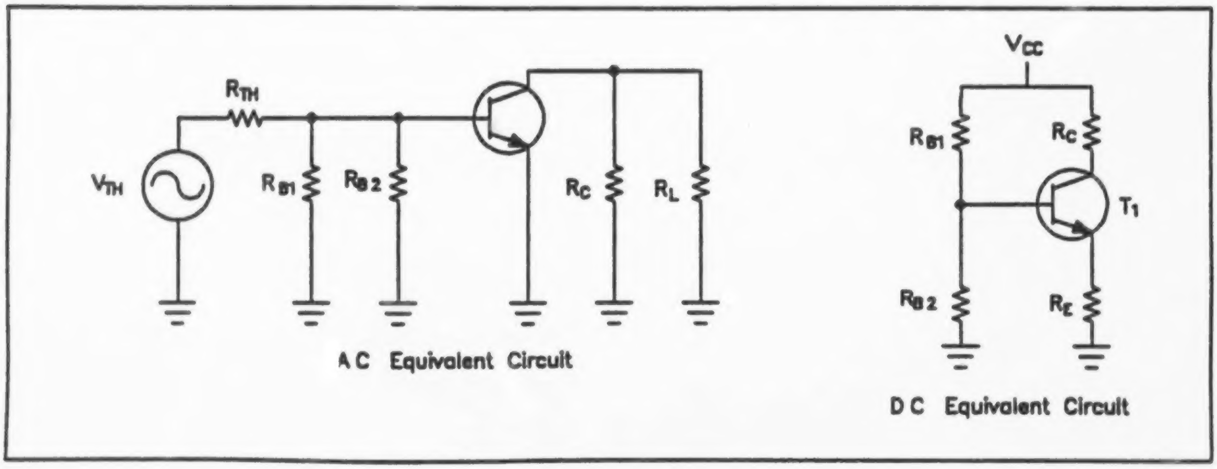

Vcc
RB1
RC
C2
RTH
C1
T1
VTH
RB2
RE
C3
RL

Single Stage Transistor Circuit

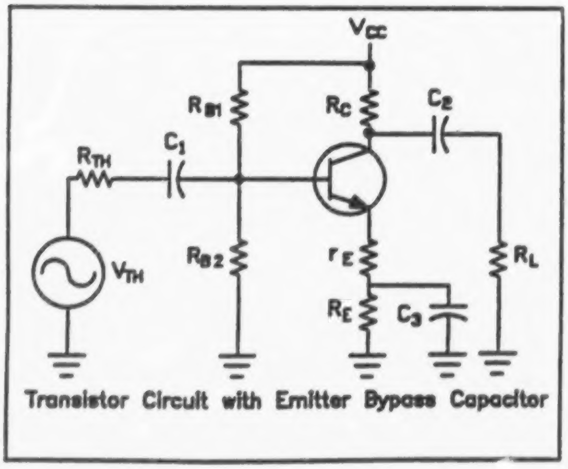
Figure 1


RTH
VTH
RB1
RB2
RC
RL
Vcc
RB1
RC
T1
RB2
RE

A C Equivalent Circuit

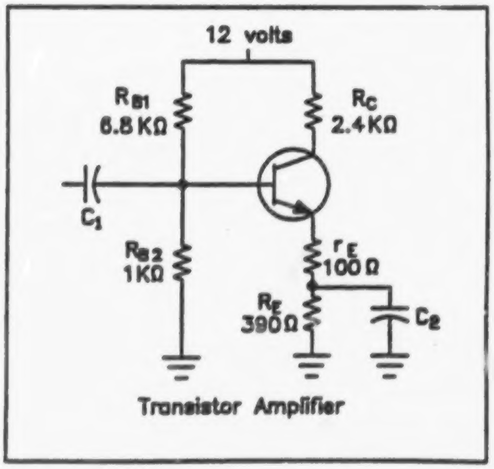
D C Equivalent Circuit

Figure 2


Vcc
RB1
RC
C2
RTH
C1
VTH
RB2
rE
RL
RE
C3

Transistor Circuit with Emitter Bypass Capacitor

Figure 3


12 volts
RB1
6.8 KΩ
RC
2.4KΩ
C1
RB2
1KΩ
rE
100 Ω
RE
390Ω
C2

Transistor Amplifier

Figure 4

across a resistance is proportional to the resistance and gain is a proportional number, then the voltage gain must be the ratio of resistances. The input signal will be across the emitter resistance, and the output signal will be across the collector resistance. We can find the voltage gain by dividing the collector resistance by the emitter resistance.

Remember that any capacitor in the circuit will show as an ac short. The capacitor that splits the emitter resistance has shorted out the bottom resistor or R_E. The resistor r_E plus the internal resistance re' are the only resistances with the input signal across them. The resistance that does not have the capacitor bypassing it is swamping the transistor stage. The input ac signal voltage is across this resistance.

Formula 3 shows the resistance that is not bypassed, r_E, plus the internal ac emitter resistance, r_e', in the denominator or bottom of the formula. The collector resistance then becomes the numerator, or the top part of the fraction.

$$A = \frac{R_C}{r_E + r_e'} \qquad \textit{formula 3}$$

In the ac equivalent circuit in figure 2, notice what the input signal sees. The input signal from R_{TH} sees the two resistors from the voltage divider in parallel with the internal resistance in the transistor and the emitter circuit. Formula 4 shows this in formula form. The input impedance is the parallel combination of the voltage divider and beta times the resistance in the emitter of the transistor circuit. The two vertical lines in the formula are a short-form method of showing "in parallel with". This is handy since you will normally use your calculator for finding the input impedance, and just knowing that they are parallel makes it easier to do the computations.

$$Z_{in} = R_{B1} \parallel R_{B2} \parallel \beta(r_E + r_e') \qquad \textit{formula 4}$$

Formula 5 shows that the output impedance of the stage is the collector resistance. You can see this in the ac equivalent circuit. This is the output impedance facing the load.

$$Z_{out} = R_C \qquad \textit{formula 5}$$

Let's take figure 3 and use the ten-step process that you learned earlier to design a transistor amplifier. A load of 3 kΩ and V_{CC} of 12 V will give us an R_C of 3 kΩ. The resistors r_E and R_E will have a combined value of 500 Ω. The voltage divider resistors R_{B1} and R_{B2} will have values of 30 kΩ for R_{B1} and 4.7 kΩ for R_{B2}. The 500 Ω for the combined resistors of r_E and R_E will have to be split between the two resistors. The more resistance we give to r_E, the less gain we will have in the stage. We can make r_E equal to 200 Ω and R_E equal to 300 Ω.

Now, using these values, we can calculate the gain of the transistor stage, the input impedance, and the output impedance. To start, we will need the emitter current. Our previous calculations gave us 1.7 mA of emitter current.

Now, using formula 2, we can find the ac emitter resistance, r_e', which is 25 divided by 1.7, or 14.7 Ω. Our emitter current was 1.7 mA, but we divided by the 1.7 and not 1.7 times 10^{-3}.

Next, we can use the r_e' and formula 3 to find the gain of the transistor in the circuit. This gain is equal to the 3 kΩ collector resistor divided by the sum of the emitter resistance that is not bypassed and the internal resistance r_e'. The 200 Ω for r_E plus the 14.7 Ω for r_e' equals 214.7 Ω. The 3 kΩ divided by 214.7 equals a gain of 14. A 1 mV signal on the base of the transistor will yield a 14 mV signal on the collector if we ignore impedance losses. You will learn more about impedance losses between stages in the next assignment.

We will use formula 4 to find the input impedance of the circuit. Since we do not know what the beta of the transistor is, we will use our standard value of 100. If you know the value of the beta for a transistor, then you should use the correct beta in the formula. The difference between a beta of 100 and 300 will not make a significant difference in the result. Using the beta of 100, the input impedance of our circuit is 3.4 kΩ.

Formula 5 shows that the output impedance of the circuit is equal to the collector resistor or 3 kΩ. The values of 3.4 kΩ for the input impedance and 3 kΩ for the output impedance are typical values for this type of circuit.

If you examine formula 3, you will note that the gain can be easily increased by reducing the value of r_E. If we moved our capacitor to bypass the resistance in the emitter, the gain would be the 3 kΩ divided by r_e', or 14.7 Ω. This would result in a gain of 204. This gain of approximately 200 is about the most that you can get from this type of circuit.

EXERCISE: Read each question carefully, and take your time. Use your notebook paper or scrap paper to solve the problems. Round off your answer to the three most significant digits.

1. What is the dc voltage V_B for the transistor in figure 4?
   A. 1.9 V
   B. 1.5 V
   C. 1.1 V
   D. 0.8 V
   E. None of the above

2. What is the value of V_E in figure 4?
   A. 1.4 V
   B. 1.2 V
   C. 0.84 V
   D. 0.70 V
   E. None of the above

3. What is the value of r_e'?
   A. 6.5 Ω
   B. 9.7 Ω
   C. 12.3 Ω
   D. 14.7 Ω
   E. None of the above

4. Find the gain for the circuit in figure 4.
   A. 21
   B. 35
   C. 16
   D. 42
   E. None of the above

B-9

Multistage Transistor Amplifiers

UNIT OBJECTIVE: Upon completion of this instructional unit, the student will be able to demonstrate a knowledge of how semiconductor devices operate and how they are used in a circuit.

SPECIFIC OBJECTIVES: Upon completion of this assignment, the student(s) will be able to demonstrate a knowledge of:

- how to calculate the voltage gain of a multiple-stage transistor circuit
- how to calculate the impedance losses in multiple-stage transistor circuits
- the class A, B, and C transistor circuits

TERMS

Darlington transistor: Two transistors with their collectors connected and the emitter of one transistor connected to the base of the other transistor.

Emitter follower: This is a transistor circuit in which the output is taken from the emitter. The circuit has unity voltage gain and low output impedance.

Decibels: A logarithmic ratio, which is used to give a value to various ratios.

DARLINGTON TRANSISTOR CIRCUITS

When you studied biasing the base of a transistor with a voltage divider, you were cautioned to have at least 10 times more current in the divider than what the base of the transistor required. The base current is equal to 1/ß times the collector current. If you could increase the values of the resistors in the voltage divider, you could increase the input impedance to the transistor stage. The beta of the transistor limits how far you can increase the resistance in the divider.

The darlington circuit, shown in figure 1, can be used to increase the beta of the transistor circuit. ***Information learned in your math courses will help you understand the concept of a darlington and how the increase in beta will affect a circuit.*** These circuits can be purchased as one component. The two transistors are inside a package that looks like one transistor. You can also make a darlington by connecting two transistors.

The darlington circuit has the same three leads coming from it that you would expect with a transistor. The voltage from the base to the emitter of the darlington is twice the voltage for a single transistor, or 1.4 V.

The darlington shown in figure 1 is being used as an emitter follower circuit. There is no advantage in using a darlington as a regular amplifier of the type you have been studying. The added beta has no effect on the gain of the circuit. Remember that the gain of an amplifier is determined by the ratio of the collector resistance to the emitter resistance.

The emitter follower circuit is a current amplifier. The high beta of an emitter follower gives this circuit a high current gain. We can assume a beta of 100 for both transistors and look at how the beta is multiplied. Starting with the second transistor, or the one on the right, we can give it a collector current of 1 A. The base current of this transistor is then 10 mA. This 10 mA is also the emitter current of the first transistor. The emitter current and collector current are the same for our purposes. By dividing this 10 mA by the 100 beta again, we will get the base current of the first transistor, which is 0.1 mA.

If we use our formula for the beta of a transistor, which is the collector current divided by the base current, and divide the total collector current by the base current of the first transistor, we will get a total beta of 10,000. You can also just multiply the betas, 100 times 100, to get the 10,000. The emitter follower circuit is able to take advantage of this, since it is a current and not a voltage amplifier. The lower level of current required in the base circuit of the darlington is usually described as a high input impedance. The darlington will give you an even lower output impedance when used as an emitter follower than just a transistor would. This makes this circuit excellent to connect between a high impedance source and a low impedance load.

The most common use for the darlington is in power supplies. The circuitry that is required to control a high amperage power supply will not have to handle as much current because of the increase in beta of the darlington.

THE EMITTER FOLLOWER

In previous assignments, the amplifiers that you studied were all class A amplifiers which amplified the voltage of the signal. The emitter follower amplifies the current and provides a low impedance output. The output impedance from an emitter follower is from 10 to 60 Ω. The circuit in figure 1 is an emitter follower circuit. The output is taken from the emitter and the collector is connected directly to V_{CC}.

The amount of resistance used for R_E has only a small effect on the parameters of the circuit. For most applications where you will use an emitter follower, you can use a 1 kΩ resistor for R_E. It is also easy to bias an emitter follower. You can set up a voltage divider to put the base voltage at anywhere from 0 to V_{CC}, which is often desirable. To get the maximum voltage output from the output of this circuit, you should set the bias voltage to the middle of V_{CC}. You can simply make the two resistors of the voltage divider the same value.

The voltage divider current should be at least 20 times the base current, just like the class A amplifiers that you have already studied. Also, the same input impedance formula that you studied earlier will work on the emitter follower. When you use this formula on an emitter follower, the part of the formula that multiplies beta times the emitter resistance will be a very large number. Remember that this part is in parallel with the resistors that you chose for the voltage divider. If these resistors are small enough to not break the 20 times current rule, then they will be small enough to control the input impedance. The large resistance from the beta times the emitter

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resistance will have little effect on the result. It is for this reason that we normally figure the input impedance of an emitter follower as the two voltage divider resistances in parallel.

The output impedance of the emitter follower is equal to the ac emitter resistance, r_e', plus a small amount. Since the emitter resistance is not bypassed and the gain is unity, there is very little distortion from this circuit. Unity gain is considered no gain or loss within the circuit.

IMPEDANCE LOSS BETWEEN STAGES

You have already learned that the gain of a transistor is determined by the ratio of resistance between the collector and emitter. To find the input impedance of a transistor circuit, you combine in parallel the resistance of the top and bottom part of the voltage divider and beta times the resistance in the emitter circuit. The output impedance is the collector resistance. Now we are ready to examine why we are concerned with the input and output impedance, when we are looking at the total gain of a circuit.

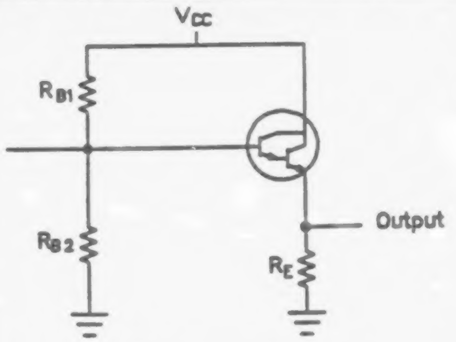
The transistor represents an increase in voltage gain within a circuit. Some of the signal voltage will be lost between stages. This will result in a total gain which is lower than the gain of the transistor by itself. In figure 2, we have a circuit that will illustrate how the signal voltage is lost. Look at the signal source as a transistor and the Z_{out} as the collector of that transistor. The Z_{in} is then the input impedance of the next stage, which could be another transistor amplifier.

The Z_{out} and Z_{in} act like two resistors in a voltage divider. Let's give the voltage source a 10 mV value. Now we want to find the amount of voltage between the two resistors or on the signal out. We can find this by dividing the sum of the Zin and Zout by Zin and then multiplying by the 10 mV voltage source.

The voltage gain over the whole circuit is the main point of interest. To find this gain over the complete circuit, we multiply the loss ratios times the gain ratios. The total gain for the circuit will be the total of all gains and losses multiplied together. For example, in figure 2, if the Z_{out} or collector resistance is 2 kΩ and the input impedance or Z_{in} is 3 kΩ, the ratio would be 0.6 and the voltage out would be 6 mV.

Figure 3 is a three-stage amplifier with the third stage an emitter follower. You have already learned how to calculate the gain of one stage and the input and output impedances. For this example, we will assign gain and impedance values to the circuit. We can start by giving T_1 a gain of 30 and the collector resistor for T_1, R_3, a value of 4 kΩ. Next the input impedance of the second stage can be 2 kΩ. This 2 kΩ divided by the sum of the 2 kΩ plus the 4 kΩ will give a ratio of 0.33. Now, multiplying the 0.33 loss ratio times the transistor gain of 30 will give a total gain of 10 so far.

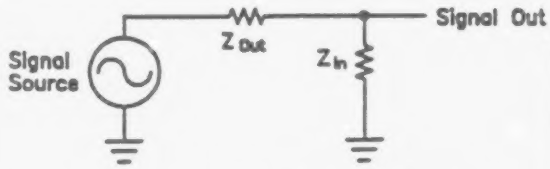
Next, we can give T_2 a gain of 40 which when multiplied by the 10 will give a gain of 400 at this point. If collector resistor R_8 is 3 kΩ, then the output impedance is 3 kΩ for the second stage. We can make the input impedance into the third stage of 4 kΩ. This will give a loss of 4/7 or 0.57. This 0.57 times the 400 yields 228. The third stage is an emitter follower which has unity gain. This unity gain times the 228 leaves 228. We have one more loss between the emitter follower and the load. If we give the emitter follower an output impedance of 30 Ω and the load 50 Ω, then the loss here is 5/8 or 0.62. This 0.62 times the 228 will give a total gain of 141. This total circuit


Vcc
R_{B1}
R_{B2}
R_E
Output

Darlington Transistor

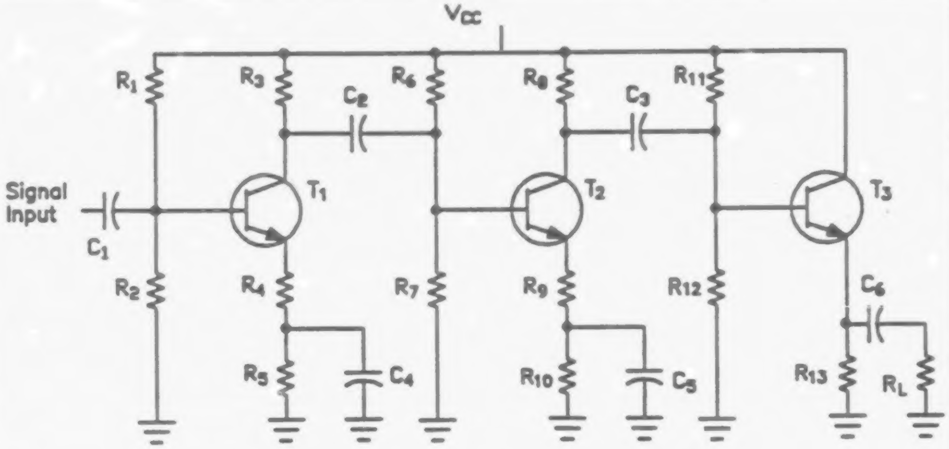
Figure 1

$$\text{Signal Out} = \frac{Z_{in}}{Z_{out} + Z_{in}} \text{ (Signal Source)}$$


Signal Source
Z_{out}
Z_{in}
Signal Out

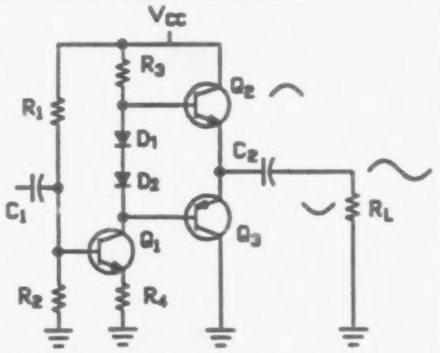
Impedance Loss Equivalent Circuit

Figure 2


Vcc
R_1
R_3
C_2
R_6
R_8
C_3
R_{11}
Signal Input
C_1
T_1
T_2
T_3
R_2
R_4
R_7
R_9
R_{12}
C_6
R_5
C_4
R_{10}
C_5
R_{13}
R_L

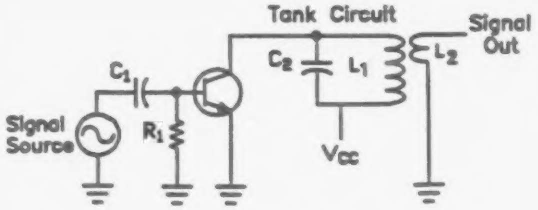
Three Stage Amplifier with Low Output Impedance

Figure 3


Vcc
R_3
R_1
Q_2
D_1
D_2
C_2
C_1
Q_3
R_L
Q_1
R_2
R_4

Class B Push Pull Amplifier

Figure 4


Tank Circuit
Signal Out
C_1
C_2
L_1
L_2
Signal Source
R_1
Vcc

Class C Tuned Amplifier

Figure 5

gain of 141 means that the input signal will be amplified 141 times. A 5 mV signal on the input will result in a 705 mV signal at the load.

DECIBELS

The use of decibels is very common in the electronics industry. A decibel is the logarithm of a ratio. This ratio can be either voltage, current, or power. Voltage and current in decibels are different from power, and the two are not interchangeable and must be kept separate.

Working with decibels (abbreviated *dB*) has become much easier with modern calculators. To find the gain in decibels of the three-stage circuit we just examined, we would take the logarithm of the gain, which is a ratio of the voltage out divided by the voltage in. The gain was 141 and the log of 141 is 2.15. Since this is voltage, we will multiply the 2.15 by 20 for a total of 43 dB. Now the circuit has a gain of 43 dB.

voltage $dB = 20\log \frac{V_1}{V_2}$ *formula 1*

current $dB = 20\log \frac{I_1}{I_2}$ *formula 2*

power $dB = 10\log \frac{P_1}{P_2}$ *formula 3*

Formulas 1, 2, and 3 will give you the decibels from the ratio. To find the ratio when you have the decibels, use formulas 4, 5, and 6.

voltage $\frac{V_1}{V_2} = \text{antilog}\left(\frac{dB}{20}\right)$ *formula 4*

current $\frac{I_1}{I_2} = \text{antilog}\left(\frac{dB}{20}\right)$ *formula 5*

power $\frac{P_1}{P_2} = \text{antilog}\left(\frac{dB}{10}\right)$ *formula 6*

Notice, in the formulas, that voltage and current use 20 and power uses 10. We multiply the individual gains and losses to find the total gain or loss of a circuit. When we use decibels, we add the decibels to get the total. A 10 dB gain in one stage plus a 5 dB gain in another stage is a total of 15 dB gain for the two stages.

If we go back over our three-stage circuit again, we had a transistor gain of 30, which is 29.5 dB, and a loss between stages of 0.33, which is -9.6 dB. Then a gain of 40 gives us 32 dB, and a loss of 0.57 gives us -4.9 dB. The loss of 0.62 gives us -4.2 dB. Adding all the decibels gives a total of 42.8 dB, which rounds off to the 43 we calculated earlier.

A term that is used often when dealing with audio levels is dBm. Remember that decibels deals with ratios. The term *dBm* is referenced to one milliwatt. If you measured 18.7 mW of audio, then you could say you have 12.7 dBm of audio. Remember that dBm is power, and you have to multiply the log by 10.

CLASS A, B, AND C AMPLIFIERS

Previous assignments have covered only the class A amplifier. There are also the class B and C amplifiers, which are commonly used, and many others that are not so common.

The difference between the class A, B, and C amplifiers is the amount of the input signal they amplify. The class A amplifier will amplify the whole signal, or the full 360 degrees of a sine wave. Remember that a sine wave can be looked at in terms of degrees. We can take one wave, and the halfway point is half of 360 degrees, or 180 degrees. The class B amplifier will amplify only half of the signal, or 180 degrees, and the class C will amplify only a small part of the signal, approximately 20 degrees.

Figure 4 shows a class B amplifier. This type is used as the final stage in audio amplifiers to drive speakers. Notice how Q_1 and Q_2 both have their emitters connected to the output. Remember that the emitter follower has its output taken from the emitter. This class B amplifier is made by using two emitter followers stacked on top of each other.

This circuit is also called a push-pull amplifier. The term *push-pull* describes the way the circuit works. Each of the two output transistors is biased at cutoff. Another way to say this is to say the transistors have their Q-point at cutoff. This means that, with no signal on the input, the two transistors are just barely turned off. A sine wave fed into the input of the circuit will be split between the two transistors. The positive part of the sine wave will turn on the top transistor, and the negative part of the sine wave will turn on the bottom transistor. Each of the transistors will amplify only half of the signal. The signal is then put back together in the common output.

Biasing transistors at cutoff has been difficult for designers in the past. It is difficult to match the components close enough, with individual components on a circuit board, to keep the circuit operating just at the cutoff point. Today, designers put most of these circuits into integrated circuits. All of the components inside an integrated circuit are on one piece of silicon. This makes all the parts very uniform in their characteristics and response to temperature differences. The final result is a very stable, high-quality push-pull circuit.

The method used to bias the push-pull circuit is the critical part of the circuit. Figure 4 shows one method of biasing the transistors. Two diodes are used to hold the bias at cutoff. As the temperature changes, the diodes will change at the same rate as the transistors and adjust the bias to keep the transistor at the cutoff point.

A problem with the older designs of push-pull circuits is crossover distortion. Crossover distortion happens when the transistors are not evenly matched. If one transistor amplifies the signal more than the other, the two signals will not match up at the output. You can see this on an oscilloscope as a flat spot where the signal crosses the zero line. The modern integrated circuits do not usually have this problem.

It is important to remember, if you are working on a push-pull circuit that used discrete components instead of an integrated circuit, and you have to replace one of the output transistors, that you should replace both of them with a matched set. You can buy matched sets of output transistors.

CLASS C TUNED AMPLIFIER

Examine the circuit in figure 5. It probably looks a little strange. The usual voltage divider bias network on the base is missing. This circuit is a class C amplifier used to amplify high-frequency signals. The input signal into this circuit will generate its own bias. Remember that the base emitter junction of a transistor is a diode junction. The positive portion of a signal will pass through the base emitter diode junction and turn on the transistor. The negative part of the signal is blocked by the base emitter junction. The negative voltage will build up during the negative part of the signal and charge the capacitor C_1. After a few cycles, the capacitor will build up a negative voltage. This negative voltage will result in only the peak of the positive part of the signal getting through to turn on the transistor.

The output from the transistor becomes short bursts of energy for each cycle that enters the circuit. These short bursts of energy are formed back into a complete sine wave by the resonant tank circuit on the output. The tank circuit is the coil L_1 and the capacitor C_2. This circuit shows inductive coupling as the method of taking the signal to the next stage. Notice that V_{CC} passes through the coil. The tank circuit is the load on the collector. This type of coupling is popular with the class C radio frequency (R.F.) circuits.

The tank circuit has to be resonant to the output frequency. Its resonant frequency must be the same as the input frequency or a multiple of the input frequency. This circuit can be used to increase the frequency of the input signal. The circuit is used to just double or triple the input frequency. Any further increase in the frequency will require too much energy input to the tank circuit. The amount of energy that is available becomes smaller as the frequency is increased.

One method that can be used to determine if a class C circuit is working is to test for the presence of a negative voltage on the base of the transistor. This may be difficult if the R.F. causes the test equipment to give false readings.

EXERCISE: Read each question carefully, and take your time. Use your notebook paper or scrap paper to solve the problems. Round off your answer to the three most significant digits.

1. What is the approximate input impedance of an emitter follower with two 10 kΩ resistors for the voltage divider on the base and a 1 kΩ resistor for the emitter resistor?
   A. 10 kΩ
   B. 5 kΩ
   C. 2 kΩ
   D. 1 kΩ
   E. None of the above

2. How many degrees of a sine wave will a class B push-pull amplifier amplify?
   A. 360°
   B. 270°

C. 180°
D. 90°
E. None of the above

3. What is the total beta of a darlington made from two transistors with betas of 75 and 250?
   A. 57380
   B. 18750
   C. 325
   D. 175
   E. None of the above

4. What is the voltage gain of a push-pull circuit with a 10 kΩ, a 1 kΩ, and two diodes in its bias network?
   A. 100
   B. 10
   C. 1
   D. 0.5
   E. None of the above

5. What is the gain in decibels for a two-stage amplifier, with a gain of 59 for the first transistor, a loss between the transistors of 0.6, and a final loss between the second transistor and the load of 0.5? The second stage is an emitter follower.
   A. 57
   B. 38
   C. 12
   D. 25
   E. None of the above

6. What is the power in watts for 36 dBm?
   A. 6.35 W
   B. 248 mW
   C. 3.98 W
   D. 1.2 W
   E. None of the above

B-10

Oscillators and Feedback

UNIT OBJECTIVE: Upon completion of this instructional unit, the student will be able to demonstrate a knowledge of how semiconductor devices operate and how they are used in a circuit.

SPECIFIC OBJECTIVES: Upon completion of this assignment, the student(s) will be able to demonstrate a knowledge of:

- oscillation
- crystal-controlled oscillators

TERMS

Oscillator: A circuit or device that produces a waveform without an input.
Piezoelectric effect: Crystals that generate a voltage when mechanical force is applied, or that expand or contract when a voltage is applied, are exhibiting the piezoelectric effect.
Crystal: Usually, a quartz crystal that is used to stabilize the frequency of an oscillator.
Ceramic filter: A ceramic device with the piezoelectric effect that is used for filtering.

OSCILLATION THEORY

If you have been in an auditorium when the speakers squealed, then you have heard a system oscillating. The system started to oscillate when someone turned up the volume on the sound system and the speakers fed sound back into the microphone causing the system to squeal. ***You studied this concept in your physics classes.***

Certain conditions have to be present before a system or a circuit will oscillate. An oscillating circuit will be an amplifier with positive feedback. The positive feedback means some or all of the output must be fed back to the input, and it must be in phase.

Figure 1 shows a block diagram of an oscillator. If the signal that is fed into the input is a 1 kHz sine wave, the amplifier will amplify this sine wave and feed it out the output. Notice that the output is fed back to the input. If the output signal is in phase with the input signal, then the circuit will continue to feed itself and operate, generating this sine wave.

A system that is oscillating will have a balance between the feedback network resistance and the gain of the amplifier. This is stated mathematically by the Barkhausen Criterion. The Barkhausen Criterion states that the gain of the amplifier times the loss of the feedback system will equal unity.

This is shown in formula 1. Formula 2 is the same as formula 1 except that it solves for the feedback loss.

$A_V B_V = 1$ *formula 1*

$B_V = \frac{1}{A_V}$ *formula 2*

If the gain of the amplifier is 10 and the circuit is oscillating, what would be the loss of the signal through the feedback network? Looking at formula 2, we can see that the loss would be 1/10 or 0.1 for the feedback network.

In our example, if the original gain of the amplifier was 20, before it started oscillating, then the gain of the amplifier would have been reduced. The gain becomes reduced as a result of driving the circuit to its maximum. The signal from the output would be clipped, resulting in a net gain of 10. It would look like a square wave instead of the original sine wave.

A resonant circuit can be added to the feedback loop which will only pass the desired frequency. This will give the maximum gain to the desired frequency in the feedback loop.

OSCILLATOR CIRCUITS

Figure 2 is an oscillator used to generate high frequencies. The frequency of this circuit is determined by C_4 and the coil above it. In figure 2, the positive feedback signal is taken off the bottom of the resonant circuit network. The bottom of the resonant circuit is the same phase as the base of the transistor. In your previous studies, you learned that the collector is 180 degrees out of phase with the base.

The two resistors R_1 and R_2 form the voltage divider that sets up the bias on the base with which you are already familiar. Notice how this circuit has been set up for maximum gain. The emitter resistor is completely bypassed.

Using a choke for the collector resistor will result in a high resistance or reactance in the collector for ac and negligent resistance to the dc feeding the transistor. Remember that a choke will increase its inductive reactance as the frequency increases. This effectively results in a high reactance in the collector circuit.

The gain of the circuit is the ratio of the reactance of the choke and the internal resistance or r_e' in the emitter. This results in a high ratio or high gain for the amplifier part of the circuit.

The frequency of oscillation is determined by the capacitor C_4 and the coil. The formula for resonant frequency appeared in previous assignments, but is included here to refresh your memory.

$f_r = \frac{1}{2\pi\sqrt{LC}}$ *formula 3*

Inductive coupling has been used to take the signal from the resonant circuit network. To keep the frequency stable, it is important to take only a small amount of the signal from the resonant network. Often a buffer network is included between the oscillator circuit and its load to keep the

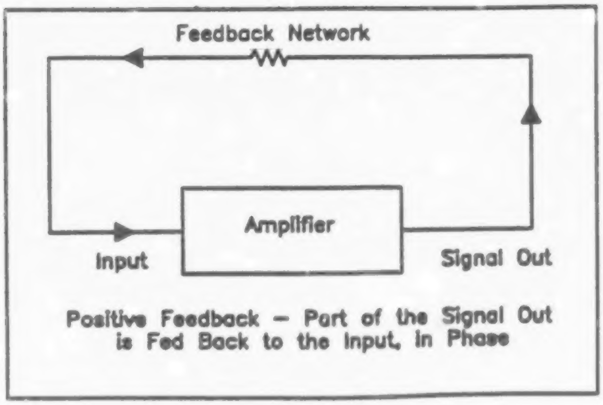

Feedback Network
Amplifier
Input
Signal Out
Positive Feedback – Part of the Signal Out is Fed Back to the Input, in Phase

Figure 1

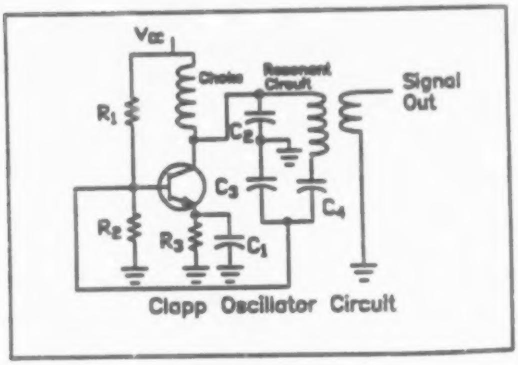

Vcc
Choke
Resonant Circuit
Signal Out
R1
C2
C3
C4
R2
R3
C1
Clapp Oscillator Circuit

Figure 2

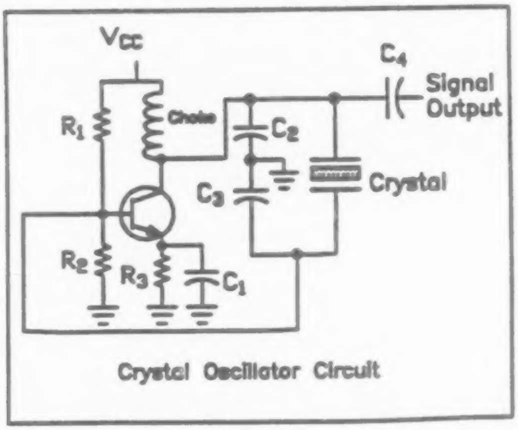

Vcc
C4
Signal Output
R1
Choke
C2
C3
Crystal
R2
R3
C1
Crystal Oscillator Circuit

Figure 3

signal taken at a constant level to stabilize the frequency. Because this type of circuit is often not stable enough for modern radio circuits, crystal-controlled oscillators are often necessary.

Figure 3 shows the circuit in figure 2 but with the coil and capacitor replaced with a crystal. With the coil gone, we have to use capacitive coupling instead of inductive coupling. The circuit still has the high gain and the positive feedback from the bottom of the resonant circuit network. The equivalent circuit for a crystal would be the coil and capacitor in series with a small amount of resistance.

The advantage of using the crystal is the very high frequency stability. There is a disadvantage of using a crystal if you have to change frequency often. This type of circuit would require that you change crystals when you change frequency.

PIEZOELECTRIC CRYSTAL DEVICES

A crystal that expands or contracts when a voltage is put across it or that generates a voltage when it is squeezed is exhibiting the *piezoelectric effect*. This piezoelectric effect is found in the crystal forms of quartz, in zinc oxide, and in lithium salts. Quartz crystal is the most commonly used material for crystals designed for electronic circuits. The quartz crystal is made by cutting a small slab from a crystal and polishing it to the proper size. The thinner the slab is, the higher the frequency will be. The equipment that polishes the slabs will monitor the frequency during the polishing operation and stop at the correct frequency.

Quartz crystals can be manufactured with resonant frequencies from 2 kHz to 200 MHz. As the size of the slab gets smaller, the device becomes more delicate, and care must be taken to avoid breaking it. When the polishing operation is completed, metal plates are attached to each side of the crystal, and the electrodes are connected. The crystal must be properly mounted inside its protective case. The frequency stability of the crystal can be harmed if the mounting is not done carefully.

The type of cut used when making a crystal will determine the crystal's frequency response. A crystal can be cut so that it will not change with temperature changes. However, such a crystal is very delicate and more costly than the regular-cut crystals.

Other methods are usually used to stabilize the frequency of a crystal circuit with changes in temperature. One way is to put the crystal in a small insulated box. A heater made from 5 watt resistors is then used to hold the temperature inside the box at a constant level. A thermostat inside the box controls the current to the resistors. This type of frequency control will hold to within very close tolerances.

One problem with putting a crystal in an oven is the time it takes to warm up and stabilize. The early radios used for communications by police and fire departments used ovens like this to keep their radios on frequency. They would turn on the radio and let it warm up for a few minutes before using the radio. This was a problem for some of the emergency services.

The need to eliminate the warm-up period resulted in a system using electronic circuitry to adjust for changes in temperature. Resistors that change their resistance with temperature are used to adjust the frequency of the crystal during temperature changes. This circuitry is usually set by using an oven and a computer to compute the amount of resistance needed. The whole package is called *TCXO,* for temperature compensated crystal oscillator. Very high levels of temperature stability have been achieved using these techniques.

When a quartz crystal is first cut, it will drift in frequency for about the first three days it is used. To solve this problem, manufacturers usually age the crystals by operating them for three days before shipping.

PIEZOELECTRIC CERAMIC DEVICES

The piezoelectric effect is very strong in some ceramic materials. These materials are manufactured in almost every size and shape, and they have become a cheaper way to build crystal filters. Ceramic filters are found in the I.F. section of most radio receivers using frequency modulation. Ceramics are also used to make transducers for depth sounders. The ceramic device will vibrate and receive audio signals in the water. High-frequency speakers and sensitive microphones are also made using ceramic crystals.

The quartz crystal can have a Q factor as high as 10,000, but ceramic filters do not have a Q that high. Remember that the Q of a resonant circuit can be considered the quality of the circuit. It is found by dividing the inductive reactance by the ac resistance of the coil.

Ceramic filters used for wide bandwidth filtering will have a Q around 400, while those used for narrow bandwidth filters have a Q around 1,500. The two-way radios that are used by businesses and operate in the 450 MHz band have a channel bandwidth of 10 kHz. These radios are frequency-modulated, which refers to the modulation method that is used to cause the frequency of the radio to change. The Federal Communications Commission has spaced the individual frequencies so that each channel is only 10 kHz, and the maximum deviation allowed is only 5 kHz. Only a crystal or ceramic filter could separate a 10 kHz channel out of 450 MHz. The ceramic filters that are used for this commercial service have a bandwidth of 7 kHz. Most FM receivers have two ceramic filters in series to get the sharp cutoff at 7 kHz that is needed to avoid picking up the adjacent channel.

Ceramic filters look like small, flat, square devices with three leads coming out of them. The center lead is ground, and the two outside leads are the input and output. A colored dot is used to identify the frequency of the individual filters. There are five different colors, so if you should ever replace one of these devices, be sure to use the same color for both filters.

UNWANTED OSCILLATIONS

A circuit that oscillates is probably the most difficult problem to troubleshoot for a technician. The problem can simply be a wire that was moved and not a broken component. Understanding how oscillation works can help in finding the problem. To find and repair an oscillation problem, you will have to locate the feedback path and break it. Remember that positive feedback is necessary to have oscillation. If you can increase the resistance to the signal in the feedback path, then you may be able to stop it from oscillating.

In an amplifier, a wire carrying the signal from the output stage, which will be strong, can come close enough to a wire feeding the input to couple the signal back to the input. The two wires can act like the two plates of a capacitor and couple the signal from the output back into the input. It is customary to run the wires in a piece of electronic equipment along the metal chassis, which will also act like a capacitor and reduce the potential for oscillation.

Sometimes capacitors in the circuit will open and result in sufficient signal being fed back to an input to cause the circuit to oscillate. Negative feedback can be used to eliminate or reduce this possibility. If the circuit has negative feedback and something fails with that circuitry, the circuit would oscillate and the gain of the circuit would be much higher.

EXERCISE: Read each question carefully, and take your time. Use your notebook paper or scrap paper to solve the problems. Round off your answer to the three most significant digits.

1. In an oscillator circuit, if the gain of the amplifier is 15, what is the loss in the feedback network?
   A. 0.7
   B. 0.3
   C. 0.07
   D. 0.03
   E. None of the above

2. If the positive feedback were coming into the emitter of a transistor, which leg of the transistor could you move this feedback to in order to get negative feedback?
   A. Move it to the base.
   B. Move it to the collector.
   C. Leave it on the emitter, and add a capacitor.
   D. It cannot be done.
   E. None of the above

3. Rank the following in descending order for the value of their Q; ceramic device, quartz crystal, coil and capacitor.
   A. Quartz crystal, ceramic device, and coil and capacitor
   B. Ceramic device, quartz crystal, and coil and capacitor
   C. Coil and capacitor, ceramic device, and quartz crystal
   D. Ceramic device, coil and capacitor, and quartz crystal
   E. None of the above

4. What do you look for when you are troubleshooting a problem oscillation?
   A. A failed component
   B. The oscillation
   C. The positive feedback path
   D. The source of power to the circuit
   E. None of the above

5. What is the equivalent circuit for a crystal?
   A. A resonant tank circuit with additional resistance
   B. A choke and capacitor combination with series resistance
   C. A series resonant circuit with a small amount of series resistance
   D. A varicap diode and a coil
   E. None of the above

6. If the impedance in a positive feedback network is doubled, what would have to happen with the amplifier to keep the oscillator going?
   A. The gain of the amplifier would have to drop by 50%.
   B. The gain of the amplifier would have to increase by 50%.
   C. The gain of the amplifier would have to double.
   D. The gain of the amplifier would have to triple.
   E. None of the above

7. Why would the manufacturer of a circuit board build a small oven on the board?
   A. To keep the transistors from getting cold
   B. To extend the life of the circuitry
   C. To maintain a constant frequency
   D. To keep the crystal from freezing
   E. None of the above

B-11

Voltage Regulation

UNIT OBJECTIVE: Upon completion of this instructional unit, the student will be able to demonstrate a knowledge of how semiconductor devices operate and how they are used in a circuit.

SPECIFIC OBJECTIVES: Upon completion of this assignment, the student(s) will be able to demonstrate a knowledge of:

- voltage regulation
- current control
- the use of integrated circuits for voltage and current control

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TERMS

Load regulation: The load regulation is the ratio of the change in voltage output compared to the nominal voltage, when the load changes from maximum to minimum.

Ripple rejection: This is a measure of the regulator's ability to reject ripple voltage.

ZENER VOLTAGE REGULATOR

Previous assignments covered the zener regulator. You learned about the importance of having series resistance to limit the current and protect the zener. The resistor R_S, in figure 1, is this series resistance that is required to limit the current.

The breakdown voltage of the zener or the value of the zener will be the regulated voltage output. The value of the resistor, R_S, can be calculated. The resistor R_S is equal to the input voltage minus the zener voltage divided by the total of the load and zener currents.

$$R_S = \frac{V_{in} - V_{zener}}{I_{load} + I_{zener}}$$ *formula 1*

Using the math you learned in algebra classes, you can compute the variation in the load voltage in a zener-regulated circuit. As the current changes in the zener, the internal resistance of the zener, or the zener impedance times that change in current, will give us the variation in the voltage across the load.

This variation in load voltage is called ripple. Formula 2 gives you a formula for finding the ripple from a zener regulated-circuit.

$V_{rip} = (Z_{zener})(I_{max} - I_{min})$ *formula 2*

The zener regulator is useful for setting a specific voltage at some point in a circuit. You would use a zener only when the load does not need very much current. Also, if the load can be disconnected while the regulator is working, then the zener must be capable of handling the full load current. If the circuit requires larger amounts of current, a zener regulator is not practical.

TRANSISTOR REGULATOR

A good voltage regulator should have a very low output impedance, the ability to hold the voltage stable, and be capable of supplying a lot of current. Using a transistor as an emitter follower in a regulator circuit is a major improvement over the zener for handling large amounts of current.

The zener regulator, shown enclosed in the dotted line in figure 2, is used as the voltage reference for the emitter follower transistor circuit. The circuit would also work with an integrated circuit supplying the reference voltage. Remember that the emitter in this circuit will be 0.7 V less than the base, and the base is set by the zener.

The emitter followers that you have studied so far have had a voltage divider feeding the base. The circuit in figure 2 has the zener taking the place of R_{B2} in the voltage divider and R_s taking the place of R_{B1}. The load is the emitter resistance R_E, and the output is taken off the emitter. This circuit will handle as much current as one transistor can handle.

These individual circuits, like the zener regulator circuit, can be thought of as building blocks. Large, more complex circuits are made using many small building blocks or smaller circuits. To show this, we have drawn a dotted line around the portion of the circuit in figure 2 that is the circuit in figure 1.

This circuit can regulate up to 50 A. Transistors that are capable of handling this level of current will have betas much lower than the small signal transistors you have studied so far. A transistor with a 50 A rating may have a beta as low as 20. Most transistor designs will not handle more than 30 A, which would be a beta of from 20 to 30.

A voltage regulator that is handling 30 A with a beta of 30 would require 1 A into the base. One ampere is a lot of current for the zener control circuitry. The zener circuit can handle it, but, if the transistor is replaced with a darlington, the base current requirements would be lower. A darlington is often used to control larger current levels. The amount of current required into the base becomes much smaller, which results in a cheaper package.

Let's put some values on the circuit in figure 2 and see how it works. We can give the load a requirement of 12 V and 3 A. The unregulated voltage feeding the circuit is 16 V. Now we can determine the value that we will need for R_s, the zener and the transistor.

The transistor must be capable of handling 3 A. We can assume a beta of 50 for this transistor. The zener voltage will be 0.7 V higher than the voltage across the load. Zeners, like most other components in electronics, are available with certain tolerances. It would be hard to find a zener at exactly 12.7 V. A 13 V zener with a 10% tolerance would be a little easier to find.

The 13 V zener, plus and minus the 10%, would give us 11.7 to 14.3 V. We will use the nominal voltage of 13 V for our calculations. The unregulated voltage on the other side of R_s is 16

V and the zener is 13 V, which gives us a 3 V drop across the resistor R_S. The 3 A required by the load is the collector current of the transistor. This 3 A divided by the beta of 50 gives a base current of 60 mA. Next, the 3 V divided by the 60 mA gives a calculated resistance of 50 Ω for R_S.

If we use exactly 50 Ω, there will be no current for the zener. We need some current for the zener as well as the transistor. One way to pick a resistor from the list of 5% values is to drop two values below the calculated value. This would give 43 Ω. If the variation in input voltage is severe, a lower value resistor may be necessary. We can use the lower value of the voltage for the calculations we have just done. A higher value of input voltage will then add more current to the zener.

To determine the current requirement of the zener, it is important to determine if the load can be disconnected. If it can, the zener needs to be capable of handling the current that passes through the series resistor R_S. This current is equal to 3 V divided by the 42 Ω or 70 mA plus the extra current from the increase in voltage on the input.

The voltage feeding into the regulator should be filtered to give 10% or less ripple. The filter capacitor after the rectifier should be increased until the ripple is at a maximum of 10%. Ten percent of 16 V is 1.6 V of ripple. A 10% level of ripple is unacceptable to most transistor circuits.

Let's apply some numbers to the ripple and examine what happens. We can give the zener an impedance of 5 Ω. The 10% ripple, which is 1.6 V, divided by R_S will cause a current change in the zener of 37 mA. Notice that the ripple changes the voltage drop across the resistor R_S. The change in current times the impedance in the zener, which is 37 mA times the 5 Ω, gives 0.19 V change in the output. A 0.19 V ripple in 12 V regulated output is 1.5% of ripple. This amount of ripple is acceptable for most circuits.

This 1.5% is called the load regulation. The load regulation is an important parameter of a power supply. The ripple rejection indicates how well the regulator rejects an incoming ripple. The ripple rejection is the ratio of output ripple to input ripple. Our example had an output ripple of 0.19 V and an input ripple of 1.6 V. The ratio of 0.19 divided by 1.6 gives 0.119, or -18 dB of ripple rejection.

CURRENT LIMITING

Notice that figure 3 is figure 2 with the added circuitry. The added circuitry is used for current limiting. The potentiometer R_V, which has been included, is used to adjust the amount of current this circuit will allow to pass. Resistor R_1 is used to sense the amount of current flowing through the line. Look at the circuitry across the base emitter junction for Q_2. Remember that the base emitter junction will have a 0.7 V drop. The resistor R_1 and the top part of the pot R_V are across the base emitter junction.

The voltage drop across R_1 will increase with an increase in current in the circuit. When the voltage drop across R_1 becomes high enough to put 0.7 V across the base emitter junction, the transistor will turn on. When the transistor Q_2 turns on, the voltage at the collector will drop. This drop in voltage will reduce the bias on transistor Q_1 and turn it off. Transistor Q_1 will reduce

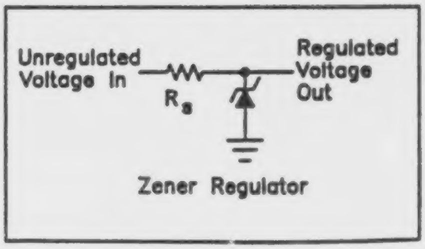
Unregulated Voltage In
Regulated Voltage Out
R_s
Zener Regulator

Figure 1

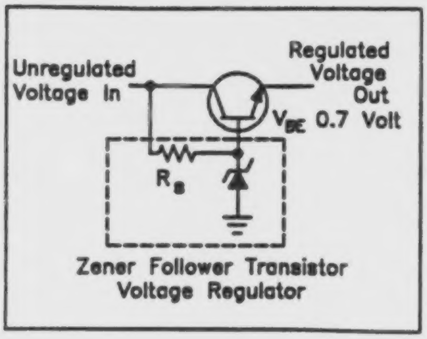
Unregulated Voltage In
Regulated Voltage Out
V_{BE} 0.7 Volt
R_s
Zener Follower Transistor Voltage Regulator

Figure 2

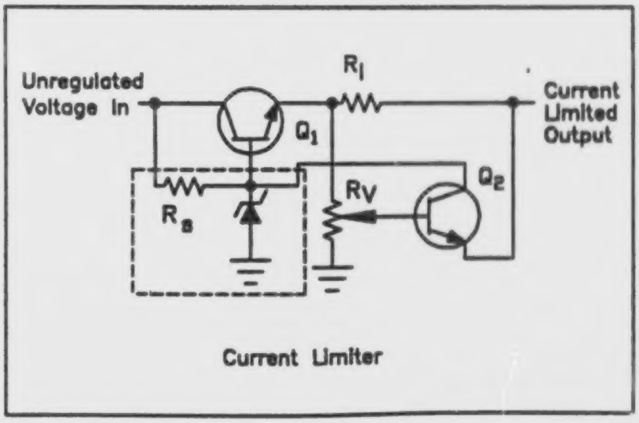
Unregulated Voltage In
R_l
Current Limited Output
Q_1
Q_2
RV
R_s
Current Limiter

Figure 3

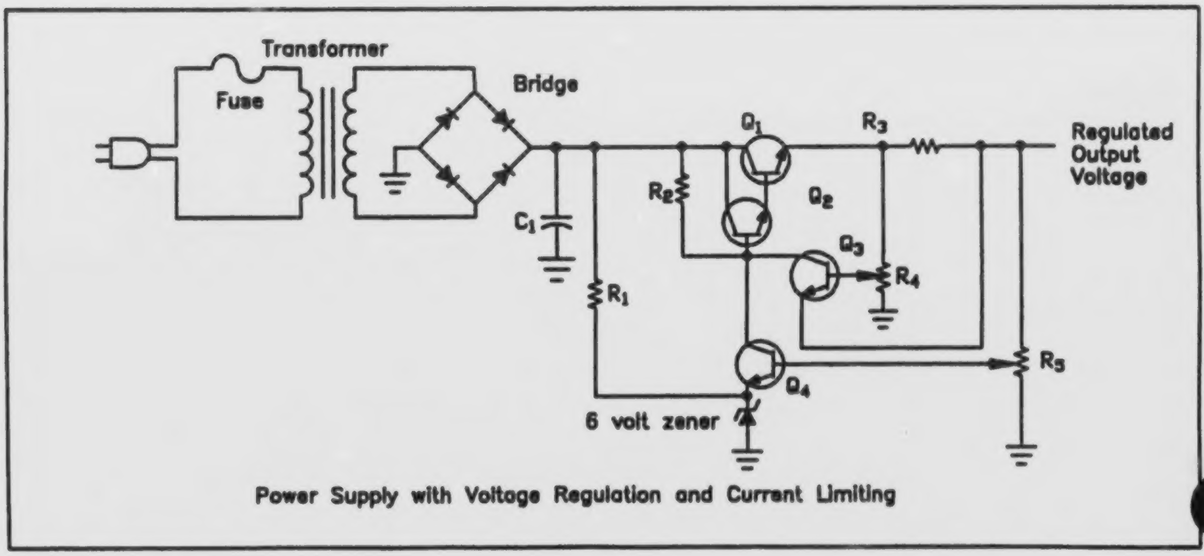
Transformer
Fuse
Bridge
Q_1
R_3
Regulated Output Voltage
R_2
Q_2
Q_3
C_1
R_4
R_1
R_5
Q_4
6 volt zener
Power Supply with Voltage Regulation and Current Limiting

Figure 4

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the voltage coming out of the circuit until the load does not require more current than the circuit will allow.

The pot R_V is used to set the amount of current that will turn on transistor Q_2 and turn off transistor Q_1. To understand how this works, let's assume that we have 16 V across R_V or 16 V coming from Q_1. Let's also assume that the amount of current that is passing through R_1 has caused a voltage drop of 2 V. Now if the wiper of the pot is set at 14 V, then the voltage drop across the emitter base junction of Q_2 will be zero. The current will have to increase the voltage drop across R_1 by another 0.7 V to turn on Q_2.

If we give resistor R_1 a value of 1 Ω, we can examine the circuit using actual values. Let us use the 16 V coming in and the load taking 2 A of current. The 2 A of current will give a 2 V drop across R_1. If the wiper on the pot is set at 14 V, then there will be 14 V on both the emitter and the base of Q_2. Now let's increase the current by 700 mA. This extra current will increase the voltage drop across R_1 by an extra 0.7 V to 2.7 V. The voltage on the base is still 14 V, but the voltage that is on the emitter and is also across the load is 2.7 V less than the 16 V, which is 13.3 V. The 14 V on the base minus the 13.3 V on the emitter gives us a 0.7 V drop across the base emitter junction of Q_2.

This is now enough of a voltage drop to turn on Q_2. To have 16 V coming from Q_1 would require a zener of 16.7 V. With Q_2 turned on, the voltage drop across R_s will be higher, causing a lower voltage at the base of Q_1. The lower voltage on the base will result in a lower voltage at the emitter and finally a lower voltage to the load. If the load is purely resistive, then less current will be required and the circuit will stabilize at the lower voltage.

If the circuit has a short or is demanding a higher level of current for some other reason, then the output voltage can go to zero without exceeding the level of current that the circuit is set for.

TOTAL POWER SUPPLY

Figure 4 includes the transformer, rectifier, and filtering discussed in previous assignments. We have also added additional circuitry to the regulator portion of the circuit. The single transistor Q_1 from figure 3 has been changed to a darlington. Notice, below the darlington, that we have Q_4, a 6 V zener, and the pot R_5. This circuitry will give us the capability of changing the regulated voltage output. The transistor Q_3 and the pot R_4 are the same circuitry for limiting the current as that in figure 3. We picked a 6 V zener because zeners at the 5 to 6 V level do not drift with temperature. This circuit allows us to change the output voltage by using R_5 and the current limit by using R_4.

To understand how we can change the voltage output, we need to look at the 6 V zener on the emitter of transistor Q_4. This puts the base of Q_4 at 6.7 V. When we adjust the wiper of the pot R5, we change the voltage divider ratio feeding the base input of Q_4. At first an increase in voltage to the base results in more current into the base. This increase in current will lower the voltage on the base of the transistor darlington pair and lower the voltage on the output. When the voltage on the output is lowered enough to put 6.7 V back on the wiper of the pot, then the circuit is stable again.

This circuit will not adjust the output voltage below 6.7 V because the base of transistor Q_4 is at 6.7 V. You could improve the circuit by adding a fixed resistor above the pot R_5 to keep from turning the voltage off when the full 6.7 V is across the pot. Also, adding a resistor to the bottom of the pot can be used to keep from turning the voltage up to the point where it is no longer regulating.

If there is ripple on the input, we would always want to have the circuit regulating the voltage output. Putting resistors on the top and bottom of the pot R_4 could be used to set up upper and lower limits to the current limiting. Variations of this circuit have been used in many commercial power supplies.

IC REGULATORS

The use of integrated circuits (IC) for voltage regulation has become more common than the other methods. These devices use very high gain circuits similar to the op-amps you will study later to provide very accurate voltage regulation. Most of the devices have current limiting and thermal shutdown. The thermal shutdown will turn the device off if the temperature inside the device gets too hot. It is very difficult to damage one of these new devices by exceeding current or voltage limits. Integrated circuits are often packaged in ordinary transistor packages. It is hard to tell them from a transistor without looking at the codes printed on the device.

A power transistor will have its collector electrically tied to the heat sink tab on the device. Integrated circuits normally have no electrical connection to the heat sink tab. This allows them to be mounted without the insulating mica and paste that is common with power transistors. The manufacturer's literature will tell you what capacitors must be added to the circuit to keep these devices from oscillating. The amplifiers inside these circuits have high gain and will oscillate if they do not have capacitors on their inputs and outputs.

SWITCHING REGULATORS

Switching regulators have an advantage over linear regulators like the one in figure 4. The linear regulator has to dissipate considerable power when passing the current on to the load. This results in bigger transistors and bigger heat sinks for larger amounts of current. Switching regulators dissipate very little power when regulating the load voltage.

The switching regulator works by switching on and off completely. It switches rapidly and usually at a frequency well above the 120 Hz of a linear circuit. This causes short bursts of current to go through a filter network, which is shown in figure 5. The diode is used to short the induced voltage caused by the rapid changes in current in the coil.

The filter network is the coil and the capacitor. This filter network will clean up the pulses of current, resulting in smooth dc with little ripple. A smaller coil and capacitor network is able to effectively filter the pulses because of the higher frequency.

The low power dissipation from the transistor is caused by the fact that the transistor does not dissipate power when it is turned off, and it dissipates very little when it is completely turned on. Remember that the power dissipated by the transistor when it is on is a function of the resistance of the transistor. When the transistor is completely on, there is a minimum of resistance.

A linear regulator, like the one in figure 4, will operate the transistor so that it maintains a level of resistance to the flow of current. This resistance is what dissipates the power and heats up the transistor. When the transistor switches on and off, there is no resistance to create the heating of the transistor.

The pulse generator, shown in the block in figure 5, uses digital techniques to generate the pulses. These pulses are then adjusted in length according to the voltage level on the output. The pulses will get longer when the voltage needs to be increased and shorter to decrease the output voltage. When the pulse is longer, the transistor will stay on longer, feeding more current to the filter network. A shorter pulse results in less current.

EXERCISE: Read each question carefully, and take your time. Use your notebook paper or scrap paper to solve the problems. Round off your answer to the three most significant digits.

1. How much resistance would you specify for the series resistor in a zener regulator circuit with an unregulated voltage of 22 V and a zener voltage of 13 V? The load on this circuit requires 50 mA. Use your calculated value.
   A. 470 Ω
   B. 180 Ω
   C. 120 Ω
   D. 47 Ω
   E. None of the above

2. What is the unregulated voltage or voltage across C_1 in figure 6?
   A. 24 V
   B. 18 V
   C. 32 V
   D. 16 V
   E. None of the above

3. In figure 6, what is the voltage, V_B, at the base of Q_4?
   A. 0.7 V
   B. 12 V
   C. 5.3 V
   D. 6.7 V
   E. None of the above

4. If the current limiting has just started in the circuit in figure 6 and there is a 2 V drop across R_3, what is the voltage from the wiper measured from R_3 to the wiper of R_4?
   A. 2.3 V
   B. 0.95 V
   C. 1.8 V
   D. 1.3 V
   E. None of the above

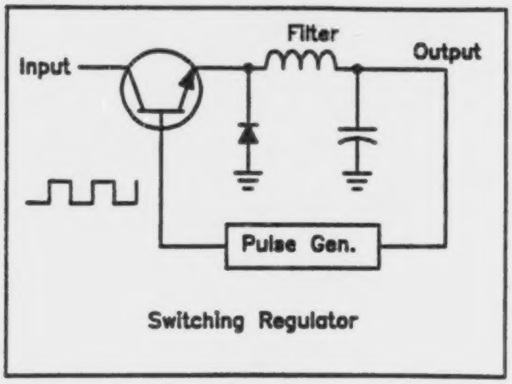

Filter
Input
Output
Pulse Gen.
Switching Regulator

Figure 5

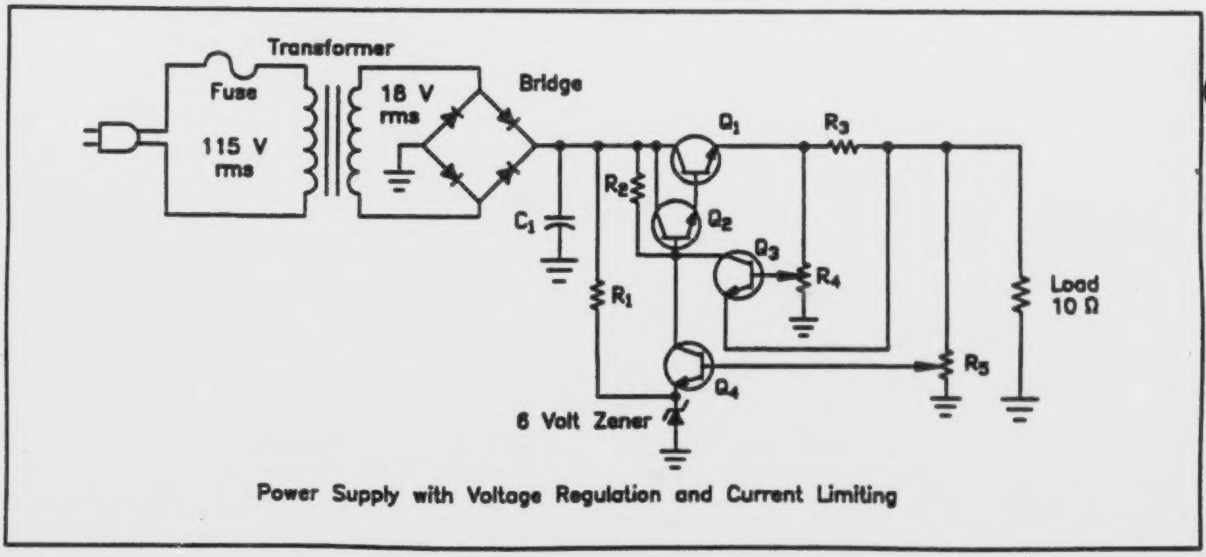

Transformer
Fuse
115 V
rms
18 V
rms
Bridge
Q_1
R_3
R_2
Q_2
C_1
Q_3
R_4
R_1
Load
10 Ω
R_5
Q_4
6 Volt Zener
Power Supply with Voltage Regulation and Current Limiting

Figure 6

5. If R_5 has been adjusted to give 9 V across the load and there is a 1 V drop across R_3, what is the voltage at the base of the darlington?
   - A. 12.1 V
   - B. 9.4 V
   - C. 6 V
   - D. 7.2 V
   - E. None of the above

6. What is the value of resistance R_3 in question 5?
   - A. 1.1 Ω
   - B. 1.8 Ω
   - C. 0.89 Ω
   - D. 0.75 Ω
   - E. None of the above

7. If the circuit in figure 6 is maintaining 9 V across the load, what size fuse should this circuit have? Remember to add 50% to your calculated value.
   - A. 0.15 A
   - B. 0.2 A
   - C. 0.5 A
   - D. 1.2 A
   - E. None of the above

B-12

Other Types of Transistors

UNIT OBJECTIVE: Upon completion of this instructional unit, the student will be able to demonstrate a knowledge of how semiconductor devices operate and how they are used in a circuit.

SPECIFIC OBJECTIVES: Upon completion of this assignment, the student(s) will be able to demonstrate a knowledge of:

- JFET transistors
- MOSFET transistors

TERMS

Unipolar: Describes a family of transistors that operate with either electron flow or hole flow, but not both.

Bipolar: Describes transistors that operate with both hole flow and electron flow.

Transconductance: Transconductance in a unipolar transistor is similar to beta in a bipolar transistor. It is the ratio of the change in output current divided by the change in input voltage.

JUNCTION FIELD EFFECT TRANSISTOR (JFET)

The bipolar transistor is the most popular discrete transistor in use today. However, there are situations where the unipolar transistor has an advantage over the bipolar in linear circuits. As you will learn later, the unipolar MOSFET is very popular in digital circuitry.

Information learned in your chemistry classes will help you understand the difference between bipolar and unipolar transistors. The bipolar transistor, which is the transistor that you have been studying, has ***both*** electron flow and hole flow. It is called bipolar because it uses both hole and electron flow. The current path travels through both N-type and P-type material. The unipolar transistor operates with ***either*** hole flow or electron flow, but not both in the same transistor. The JFET is part of the unipolar family of transistors.

A JFET is made from a small bar of semiconductor material, which may be either P-type or N-type material. We will use the N-channel transistor in our discussions, which is the transistor with the bar of N-type material. The only difference between the N-channel and P-channel transistors is the polarity. This is similar to the difference between an NPN and a PNP transistor.

Figure 1 shows how an N-channel JFET is constructed and the schematic symbol for the transistor to its right. Figure 1 shows the bar of N-type material with the two islands of P-type material. A wire is attached to both islands of the P-type material and brought out of the transistor as the *gate* lead. Two other leads come from each end of the bar of material. One lead is called the *drain*, and the other lead is called the *source*.

Remember that when N-type and P-type material are fused together, a diode junction exists. In the JFET, a diode junction exists between the islands of P-type material and the main bar of material. A diode junction means there is a depletion layer. Notice that the depletion layer takes space in the middle of the bar.

Figure 1 shows the voltage source, V_{GG}, reverse-biasing the diode junction. This reverse-biased junction means that, except for a very small amount of leakage, no current flows into the gate of a JFET. It is important to keep the gate reverse-biased with respect to the source.

As the reverse bias on a diode increases, the depletion layer increases in size. This same condition occurs with the diode junction of the JFET. As the negative bias on the gate is increased, the depletion layers from both sides of the bar increase. As they increase, the amount of area left for the electrons to flow through the device becomes smaller, causing an increase in the resistance. The negative voltage on the gate can be increased until the depletion layers touch. This will stop the flow of current or pinch off the current.

Notice that, in discussing the JFET, we talk about the voltage on the gate controlling the current. In a bipolar transistor, we talked about the base current controlling the collector current. The JFET, like all unipolar devices, is a voltage-controlled device. The bipolar transistor is a current-controlled device.

This difference between voltage and current means that the JFET has a much higher input impedance than the bipolar transistor. This high input impedance for a JFET results in no conduction of current into the gate except for some leakage. The input impedance of a JFET is in the hundreds of megohms range.

The current through the bar of the JFET is called the drain current and labeled I_D. The gate voltage that controls I_D is V_{GS}. The voltage V_{GS}, which is from the gate to the source, is like the base emitter junction in a bipolar transistor. The voltage that pinches off the drain current is labeled V_{GSoff}.

In many circuits the JFET is used with voltage divider bias like the bipolar transistor. Another method of biasing a JFET takes advantage of the high input impedance of the device. This high input impedance allows the JFET to use self-bias. Figure 2 shows the self-bias circuitry for a JFET. Notice the resistor to ground the gate but no current source feeding the gate. Because of the high input impedance, the gate voltage is at zero with respect to ground. Now look at the drain current that passes through R_S. It will give a voltage drop across R_S. If R_S is a 1 kΩ resistor and there is 4 mA of drain current, then this voltage drop will be 4 V. The 4 V drop across R_S means there is 4 V at the source of the JFET. If you measure the voltage at the gate of the JFET, with respect to the source, you will see a -4 V. This is how the negative gate bias is created.

As the current increases through the JFET, the voltage drop across R_S will increase. The increase in voltage at the top of the source resistor or at the source will increase the negative bias on the gate. This increase in negative bias will reduce the area left for the flow of current. The reduced area for the flow of current will lower the amount of current and bring the bias back to a lower level. This action will stabilize the transistor and hold the bias steady.

The JFET will not allow an unlimited amount of current to flow. The maximum amount of current that the JFET will allow to flow results when the gate is connected directly to the source. When the gate and source are tied together, the V_{GS} is zero, and it is called V_{GSon}. This current level is called I_{DSS}. The subscripts DSS stand for drain and source with the gate *shorted*. When the third subscript is an S, it stands for the third lead shorted. If the third subscript is an O, it would stand for the third lead *open*.

Formula 1 can be used to find the value for R_S. The formula shows that we use Ohm's law and divide the pinchoff voltage by the saturation current.

$$R_S = \frac{|V_{GSoff}|}{I_{DSS}} \quad \textit{formula 1}$$

The V_{GSoff} and I_{DSS} are usually easy to find for a particular device. Figure 2 was drawn with a drain resistor. A drain resistor would be needed if we were going to take the signal off the drain. This is the usual method if we want some voltage gain in the circuit. The problem with the JFET is that the current requirements and resistor requirements make it difficult to get enough gain to offset the impedance losses. It is usually better to use the device as a source follower. Some voltage gain can be achieved if the source voltage is high enough. A higher voltage from V_{DD} will allow you to use resistors that do not result in impedance losses that eat up the gain of the circuit.

The feature of the JFET that limits the current to a specific maximum allows the JFET to be used as a constant current diode. When the gate is connected to the source, the JFET will only allow a certain maximum amount of current to flow through it. These JFETs are packaged as constant current diodes with only the two leads coming out of the package.

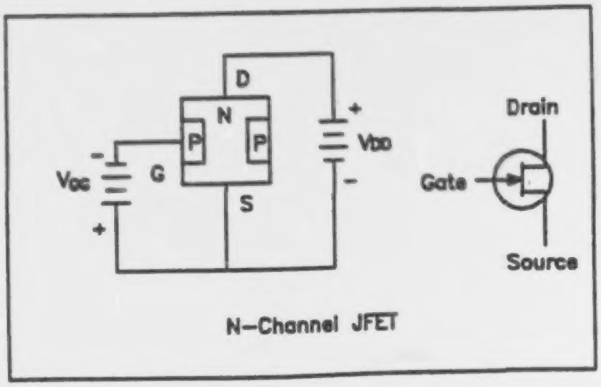
Another important feature of the JFET and all other FETs is their distortion or nonlinear amplification. The JFET has what is called square law distortion. This term comes from the transconductance curve which is parabolic. This nonlinear amplification allows the JFET to be used in mixers in radio receivers. The mixer circuit requires a nonlinear amplifier to mix the two frequencies and get the sum and difference. You will learn more about mixing later.

The JFET can be used as a solid-state switch or as a voltage-controlled resistance. If it is biased at V_{GS} equal to 0 or below V_{GSoff}, then it will operate as a switch. If the bias is varied between cutoff and saturation, it will operate as a voltage-controlled resistance. When the JFET is in saturation, the resistance from the drain to the source is called R_{DSon}. The value of R_{DSon} is usually around 100 to 200 Ω. The value of the resistance when the JFET is off is in the hundreds of thousands of ohms.

MOSFET TRANSISTORS

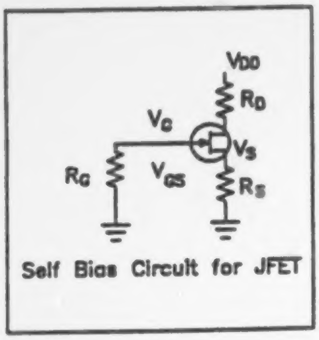
The MOSFET (metal oxide semiconductor field effect transistor) has a gate, drain, and source just like the JFET. The primary difference between the two is that the MOSFET gate is insulated from the bar or channel. Most MOSFETs are found in integrated circuits. It is possible to obtain individual MOSFET transistors. They are primarily found in computer memory circuits.

Figure 4 shows a depletion-type MOSFET. This transistor is made by putting a section of P-type material into the N-type material. This creates a narrow channel beside the P region for the electron flow. Notice how the P region forces the electrons to pass over against the gate area.


D
N
P
P
G
S
VGG
VDD
+
-
Drain
Gate
Source

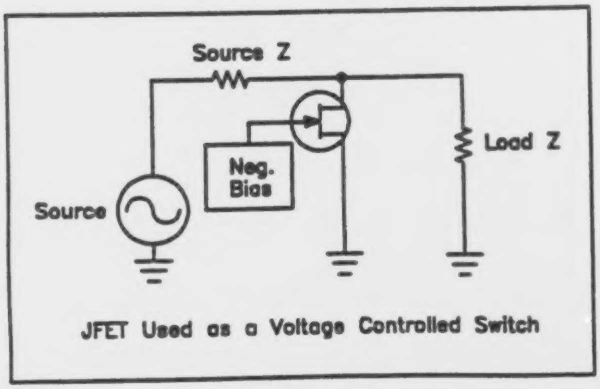
N-Channel JFET

Figure 1


VDD
RD
VG
VS
RG
VGS
RS

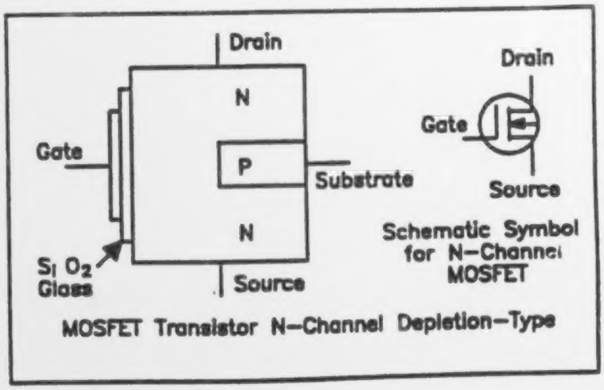
Self Bias Circuit for JFET

Figure 2


Source Z
Load Z
Neg. Bias
Source

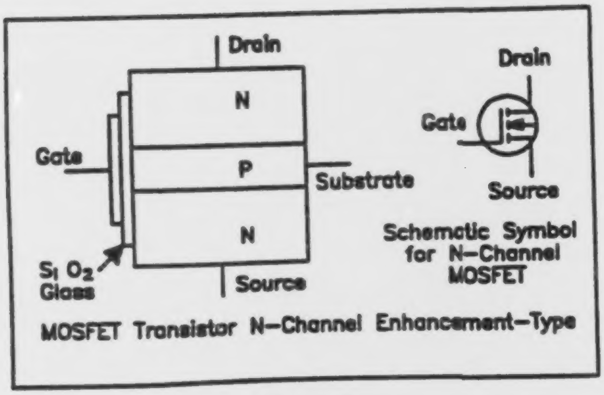
JFET Used as a Voltage Controlled Switch

Figure 3


Drain
N
P
N
Gate
Substrate
Source
Si O2 Glass
Drain
Gate
Source
Schematic Symbol for N-Channel MOSFET

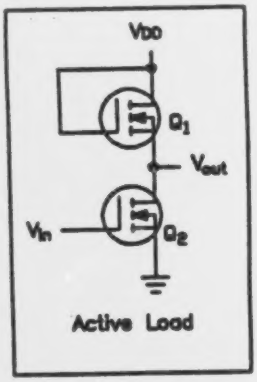
MOSFET Transistor N-Channel Depletion-Type

Figure 4


Drain
N
P
N
Gate
Substrate
Source
Si O2 Glass
Drain
Gate
Source
Schematic Symbol for N-Channel MOSFET

MOSFET Transistor N-Channel Enhancement-Type

Figure 5


VDD
Q1
Vout
Vin
Q2

Active Load

Figure 6

An N-channel MOSFET is made by first making a channel of N-type material with the section of P-type material in it. Then the gate area is made by blowing pure oxygen on it under high temperature conditions. This will oxidize the silicon. The oxygen combines with the silicon and forms silicon dioxide. Silicon dioxide is glass, which is a good insulator. Next, a layer of metal is deposited on the thin layer of glass. A lead is then welded to the layer of metal. This lead is the gate input. The glass insulator between the gate and the N-type material will stop any electrons from passing into the channel. This results in an extremely high input impedance for dc currents.

The P region, which is called the substrate, is often connected to the source. This will reverse-bias the PN junction and create a depletion area. When the gate is biased with a negative voltage, the electrons act to repel other electrons and create a depletion area from the gate outward towards the P region. A high enough negative voltage will create a depletion area all the way to the P region's depletion area and shut off the flow of electrons. This operation is similar to the JFET without the diode junction.

Unlike the JFET, the gate voltage can go positive on a MOSFET without damaging the device. A positive voltage will increase the current flow through the device. The JFET does have a little leakage on its gate lead. The MOSFET has the glass insulator, which results in no effective leakage. This means the input impedance of the MOSFET is very high. Manufacturers list the input impedance in the area of 10 million MΩ.

The terms *depletion mode* and *enhancement mode* for the MOSFET refer to the bias on the gate. The depletion mode involves a negative bias on the gate, which uses the depletion area to control the current flow. The enhancement mode is a positive voltage on the gate, which enhances the flow of electrons. The MOSFET in figure 4 can be operated in either the depletion mode or the enhancement mode. It is usually operated with a negative voltage, which puts it in the depletion mode. All of the biasing methods discussed with the JFET will apply to this device. This MOSFET can be operated with no bias at all. Another MOSFET has been developed that is particularly suited to computer circuits.

Notice how the MOSFET in figure 5 is constructed. It has the P region all the way across to the gate. This is an enhancement-type MOSFET. You will find these devices used primarily in computer chips or integrated circuits. When the gate voltage, V_{GS}, is negative or below the positive turn on voltage, there is no current flow through the device. For current to flow, a positive voltage strong enough to attract electrons into the P region is necessary. When these electrons are attracted into the P region, they form a path for the current to flow. A positive voltage on the gate with enough voltage is necessary for current flow.

The voltage for which a MOSFET is usually designed to turn on is around 3 V. This design is valuable in computer circuits because it gives the circuit a clear indication between an *off* voltage and an *on* voltage. Computer circuits operate with around 0 V for *off* and close to 5 V for *on*. Since there are many variations in the voltages, a MOSFET input to a digital device that recognizes a voltage above 3 V as "on" and a voltage below 3 V as "off" will not give a false response.

It is easier and cheaper to build integrated circuits all out of individual transistors. If the IC has only one type of transistor, it is easier to make. An IC that uses MOSFETs, like figure 5, should have only MOSFETs and no resistors, capacitors, or coils. Look at figure 6 and notice how another active device or MOSFET is used for the drain resistor. The gate on the MOSFET used for

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the load is connected to the voltage source, V_{DD}. When the MOSFET is used as a load this way, it is built with a higher R_{DSon}.

The VMOS (vertical metal oxide semiconductor) is another MOSFET-type device that has been designed for power applications. Most MOSFETs are able to handle very little power. The VMOS is designed as an enhancement device. This means it will operate with a positive voltage on the gate. Bipolar transistors have a positive temperature coefficient. That is, they will increase their beta or increase their collector current as they increase in temperature. Since more current will generate heat, the transistor runs the risk of burning up in what is called *thermal runaway*. The VMOS has a negative temperature coefficient. The VMOS will reduce its drain current when it gets hot.

The VMOS can also be used in parallel, in regulator circuits, to increase the total current. The bipolar transistor will not work in parallel. A bipolar transistor working in parallel with another bipolar transistor will tend to hog the current and burn out. They do not share the current with the other transistors. The VMOS is an expensive alternative to a power transistor, but often a better one.

STATIC PROBLEMS

One of the major industry-wide problems with MOSFETs is caused by their very high input impedance. Remember that, when the device is made, a thin layer of glass is deposited to insulate the gate from the channel. This glass insulator on the gate can resist approximately 50 V. If there is a voltage high enough to arc through the glass on the gate of the device, the MOSFET will be destroyed. The static electricity that you feel when walking on a rug and touching a doorknob is a much higher voltage than 50 V. The static buildup on your body can easily destroy a MOSFET.

The manufacturers always ship these devices with some kind of static protection. They may use foam with carbon mixed in it to provide a conducting path for the static charge or numerous other methods to drain off the static charge. Workers who assemble MOSFETs into printed circuit boards are usually required to wear wrist straps that are grounded to the bench or table where they work. Special floor mats and mats on the work bench are used to drain off the static charges. Some of the smaller devices have a wire loop wrapped around the leads coming from the device. This will short the leads together and eliminate a voltage between the gate and the source.

If you handle MOSFET devices, remember to avoid touching the leads, and use any protective straps or pads that may be available.

EXERCISE: Read each question carefully, and take your time. Use your notebook paper or scrap paper to solve the problems. Round off your answer to the three most significant digits.

1. A JFET that is made from a bar of P-type material with islands of N-type material is called—
   A. PN channel
   B. P-channel
   C. N channel
   D. Constant current diode

E. None of the above

2. An N-channel JFET will need what voltage on its gate to operate as a linear amplifier?
   A. From 4 to 6 V
   B. V_{GSoff}
   C. Half of V_{DD}
   D. Negative
   E. None of the above

3. What is the voltage on the gate when the depletion layer pinches off the current flow?
   A. +12 V
   B. V_{GSoff}
   C. I_{DSS} times R_{DSon}
   D. 3.5 V
   E. None of the above

4. What is the term for the maximum amount of current a JFET can conduct?
   A. I_{DSS}
   B. I_{Dmax}
   C. I_{Csat}
   D. I_{DS}
   E. None of the above

5. What is the formula for calculating R_S in a self-biased JFET?
   A. $RS = I_{DSS}/V_{GSoff}$
   B. $RS = V_{GSoff}/R_{DSon}$
   C. $RS = I_{DSS} \cdot R_{DSon}$
   D. $R_S = V_{GSoff}/I_{DSS}$
   E. None of the above

6. How is a constant current diode made?
   A. It is made by fusing N-type material to P-type material.
   B. The gate of a JFET is connected to its source.
   C. It is made from power supply circuits in an integrated circuit package.
   D. A transistor circuit is encapsulated into a diode package.
   E. None of the above

7. What is a safe level of gate current that a MOSFET can handle?
   A. 5 µA
   B. 10 mA
   C. 0.01 µA
   D. 0.001 µA
   E. None of the above

B-13

Thyristors

UNIT OBJECTIVE: Upon completion of this instructional unit, the student will be able to demonstrate a knowledge of how semiconductor devices operate and how they are used in a circuit.

SPECIFIC OBJECTIVES: Upon completion of this assignment, the student(s) will be able to demonstrate a knowledge of:

- the family of SCR devices
- how to troubleshoot SCR-type devices

TERMS

Breakover: Breakover occurs when a large amount of supply voltage causes a thyristor to turn on.

Thyristor: A four-layer diode used for switching high currents. It uses internal feedback to latch when switched.

SILICON-CONTROLLED RECTIFIER (SCR)

The family of thyristors includes the SCR, or silicon-controlled rectifier. ***Your studies in chemistry and physic classes will help you understand how the thyristor family of devices works***. The SCR is one of the most popular switches in the thyristor family, and it is only used for switching.

Figure 1 shows the schematic symbol for an SCR and its internal construction. The two ends are identified like a diode, with the terms *anode* and *cathode*. The internal construction shows that the thyristor is made with four layers of semiconductor material. Some of these devices will have a gate lead on the side like the SCR, and some are just diodes without a gate lead. These four layers in the SCR behave like two transistors.

Figure 2 shows the two transistors as an equivalent circuit for the SCR. When power is first applied to the device, there is no current flow on the base of each transistor. No current flow on the base means no current through the collector emitter junctions. Each of the two transistors will hold the other one in the off state.

When we apply a small amount of current to the gate lead, the lower transistor will start to turn on. The small amount of current through the lower transistor's collector emitter path will draw a small amount of current from the base lead of the transistor on top. This small amount of current from the base lead on the top transistor will result in current through that transistor's collector emitter path directly into the base of the lower transistor. Now the amount of current feeding into the base of the lower transistor has increased. This larger amount of base current turns the lower transistor on harder, which in turn causes the upper transistor to turn on harder. The two transistors drive each other into saturation very quickly. This process of reinforcement is called *positive feedback.*

The action will reverse itself if we apply a reverse bias to the gate lead when the SCR is conducting. Another way to turn on these devices is by increasing the voltage across the device until one of the transistors goes into breakdown. Remember that breakdown in a transistor resulted in an increase in current. This same breakdown action is called *breakover* when we are discussing the thyristor family of devices. The breakover of one transistor will feed current into the base of the other transistor and cause the device to rapidly begin conducting.

A minimum amount of current is necessary to keep the device turned on. This minimum level of current is called the *holding current.* If the current drops below this level, the device will turn off. When the device is used to control ac, it will turn off every time the current goes through zero. This will happen twice in each cycle. However, since the SCR is a diode and only conducts one way, this adds to the turn off as well as the current naturally dropping to zero.

The SCR only conducts in one direction. The **triac**, which is two SCRs in parallel and pointing in opposite directions, will conduct in both directions. The triac will turn off as the current passes the zero line each time.

Look at figure 1, and you will see that the P-type material at the top of the stack is the emitter of the top transistor in figure 2. The N-type material below it is both the base of the top transistor and the collector of the bottom transistor. Figure 2 shows how they are connected. The third layer down, which is P-type material, is the collector of the top transistor and the base of the bottom transistor. The same material for both transistors results in the equivalent connection shown in figure 2. Finally, the N-type material on the bottom of the stack is the emitter of the bottom transistor.

There are many different variations within the thyristor family. Some have no gate lead, and these are turned on by breakover and turned off by low current dropout.

The SCR, which does have a gate, requires a minimum of 0.7 V to turn it on. The amount of current that a SCR will require in its gate lead will depend on the capacity of the device. The data sheet that comes with the device will usually list the gate voltage and current requirements to turn the device on.

The 2N4441 SCR, which can handle 8 A, will require 10 mA of gate current to turn it on. It also has a holding current specification of 10 mA. The C701, which can conduct 1,250 A, requires 500 mA of gate current to turn it on, and a holding current requirement of 500 mA.

The critical rate of rise can be a problem with SCRs. When an SCR is in the off condition and it receives a strong noise pulse, it may turn on. The SCR will turn on as a result of the internal capacitive coupling between the anode and the gate. A filter made from a capacitor and resistor can be used to reduce any noise pulses from reaching this critical rate of rise and turning on the SCR prematurely. The 2N4441 has a critical rate of rise of 50 V/μs. The device may turn on if it receives a noise pulse that results in a voltage increase faster than 50 V/μs.

SCR APPLICATIONS

A common application of the SCR is to control the amount of current to lights and motors. The SCR will change the amount of current fed to the load by switching on at different points in the cycle. It turns off from low current dropout when the sine wave goes through the zero point. When more current is required, the SCR can be made to trigger closer to the beginning of the cycle. This will send more of the complete cycle to the load.

This control will generate a lot of electrical noise as a result of chopping up the sine wave. The rapid switching and the chopped up sine wave result in high-frequency noise that can interfere with radio receivers. Capacitors with a high reactance to 60 Hz and a low reactance to the high-frequency noise can be used to reduce the amount of noise transmitted.

When electricity was first introduced to manufacturing facilities, a lot of the things we take for granted did not exist. The first electric motors were installed to replace belt-driven pulleys. Usually, bare wires ran to the motor to supply the electricity, and the motors were the most expensive item in the system.

If an operator of an electric motor had noticed smoke coming from the motor, it would have been important to shut it down quickly. Because of the high inductive load of the motor, ordinary switches would result in arcing. Remember the induced voltage that is generated by an inductor when the current is changed rapidly. To save the motor, the operator would have thrown a metal crowbar down across the wires carrying the current feeding the motor to quickly shut it off. The crowbar would have shorted out the supply and hopefully blown the fuse, saving the motor from any additional damage. We are a little more sophisticated now, but the principle in the SCR crowbar circuit is the same.

The SCR *crowbar circuit* is used to rapidly disconnect power from a load when the sensing circuit sees a problem. The crowbar circuit can be designed to sense a high current condition or, as in the example in figure 3, a higher voltage condition coming from the supply.

Computers operate at very specific voltage levels. If the voltage coming from the power supply is excessive, many of the chips in the computer can be destroyed. The cost of a computer and possibly of some of the data in that computer will far exceed the cost of the power supply that destroyed it.

Figure 3 shows a circuit designed to short the output of the power supply if the voltage exceeds a level set by the potentiometer. The 6 V zener is the voltage reference for the circuit. We used a 6 V zener because it will maintain its voltage with changes in temperature. The triangle labeled comparator will switch its output according to the voltages on the two inputs. The circuit has put the zener voltage of 6 V on the negative or inverting input. The pot can be used to set the voltage on the positive input.

With a normal voltage on the output of this circuit, the pot should be set to a voltage slightly below 6 V. Then when a failure occurs and the regulated voltage climbs, the voltage on the wiper of the pot will climb also. When the voltage goes above 6 V on the wiper and on the positive input to the comparator, the comparator will switch high on its output and trigger the SCR. The SCR will then act as a short and draw sufficient current to rapidly blow the fuse.

A technician can troubleshoot the problem in the power supply that caused the overvoltage and repair it. Then the fuse can be changed and the power supply put back in service.

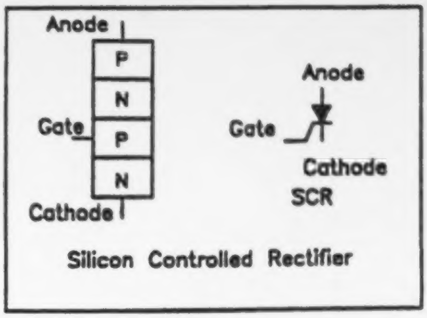
Anode
P
N
Gate
P
N
Cathode
Anode
Gate
Cathode
SCR
Silicon Controlled Rectifier

Figure 1

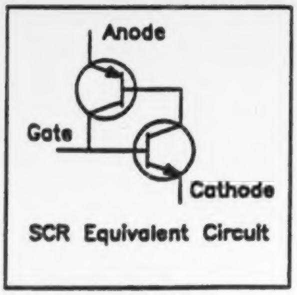
Anode
Gate
Cathode
SCR Equivalent Circuit

Figure 2

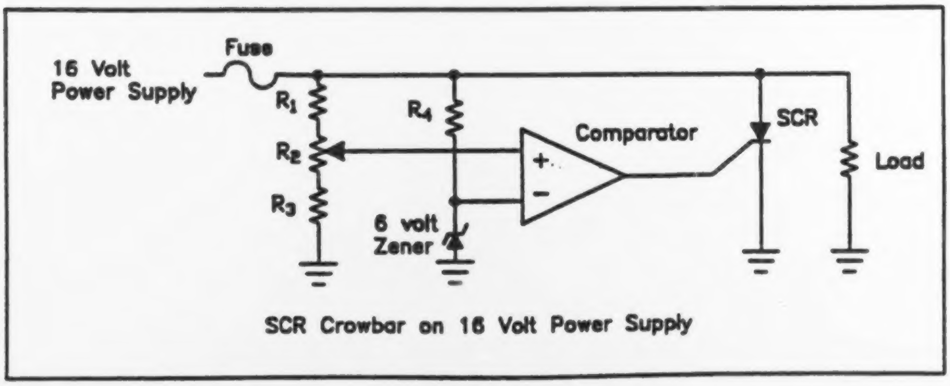
Fuse
16 Volt
Power Supply
R1
R2
R3
R4
Comparator
+
−
6 volt
Zener
SCR
Load
SCR Crowbar on 16 Volt Power Supply

Figure 3

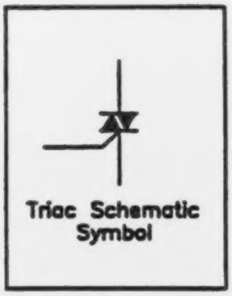
Triac Schematic
Symbol

Figure 4

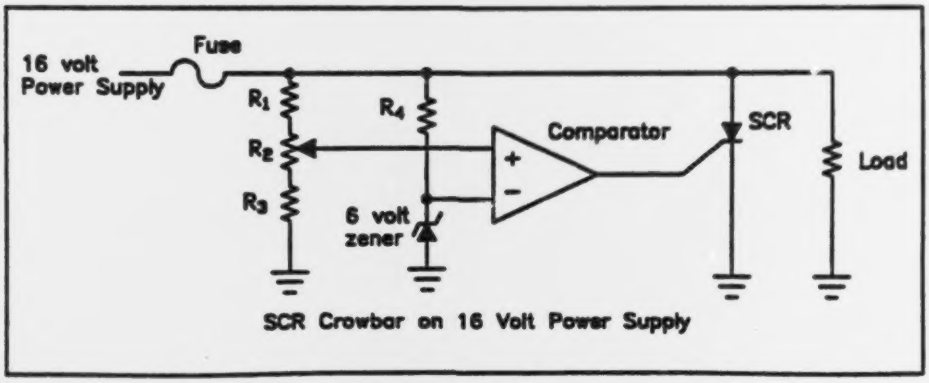
Fuse
16 volt
Power Supply
R1
R2
R3
R4
Comparator
+
−
6 volt
zener
SCR
Load
SCR Crowbar on 16 Volt Power Supply

Figure 5

This circuit is an extreme measure, designed to protect the computer. The reason for using this kind of circuit for protection is the high speed at which it reacts to the problem. This circuit is also a very reliable method of shutting down the power supply quickly.

TRIAC

Up to this point we have talked about SCRs and other devices that conduct in only one direction. The triac will conduct in both directions. This device is basically two SCRs in parallel, with each diode pointing in the opposite direction. One gate lead coming out of the device is attached to both diodes inside the package. Notice the schematic symbol for a triac in figure 4.

To turn on a triac requires a positive bias for one side and a negative bias for the other side. To switch on both the positive and negative parts of a sine wave would require both a positive and negative bias at the proper times, fed into the trigger input. With this bias, the triac can control both the positive and the negative sides of the sine wave.

UNIJUNCTION TRANSISTOR (UJT)

The unijunction transistor is often used to trigger a triac or SCR. It has three leads, two of which are labeled as bases and one as an emitter. The emitter is a small area in the semiconductor which is heavily doped. The base area is lightly doped, with the leads at each end.

Because the base area is lightly doped, there is a high resistance between the two base leads. The resistance can be from 5 to 10 kΩ. The intrinsic standoff ratio for the UJT is the ratio of the resistance between the emitter lead and the lower base or R_1 and the total resistance between the base leads labeled R_{BB}. This is simply the voltage divider ratio if you think of the UJT resistance between the bases as two resistors.

When the UJT is in the off condition, there will be a voltage across the bases that depends on this high resistance of from 5 to 10 kΩ. When a voltage appears on the emitter that is high enough to forward-bias the emitter base junction, it will conduct, and the effective resistance of the lower part of the base or R_1 will drop. The voltage between the emitter and the lower base lead will become small, and the emitter current will increase. The UJT will continue to conduct or stay latched with emitter current until the emitter current level drops below the holding current level.

EXERCISE: Read each question carefully, and take your time. Use your notebook paper or scrap paper to solve the problems. Round off your answer to the three most significant digits.

1. What is the minimum gate voltage that will turn on an SCR?
   A. 0.2 V
   B. 0.7 V
   C. 1.4 V
   D. 3.75 V
   E. None of the above

2. Which of the following changes would allow the circuit in figure 5 to work with a 5 V power supply?
   A. Change the value of resistor R_4.
   B. Change the SCR to one that will work with this small voltage.
   C. Change resistors R_1 and R_3 to correct the limits.
   D. Change the zener to something less than 5 V.
   E. None of the above

3. If the crowbar circuit in figure 5 was set to trigger at 12 V by adjusting the potentiometer while the circuit was at 12 V, what would be the voltage of the wiper of the pot if the supply jumped to 24 V?
   A. 6 V
   B. 12 V
   C. 24 V
   D. 18 V
   E. None of the above

4. How many times would an SCR have to be triggered during three cycles of a sine wave to keep it conducting?
   A. 1 time
   B. 2 times
   C. 3 times
   D. 4 times
   E. None of the above

5. Which of the following methods would force an SCR to turn on?
   A. Momentarily short the anode to ground.
   B. Use some high-voltage pulses feeding the line into the SCR.
   C. Suddenly reduce the current into the SCR.
   D. Induce a mechanical shock to the device.
   E. None of the above

6. A solid-state relay is a circuit made to operate like a relay and frequently used to replace a conventional relay. If the solid-state relay is made using SCRs, how many SCRs would it take to make a four-pole, single-throw relay?
   A. Two SCRs
   B. Three SCRs
   C. Four SCRs
   D. Five SCRs
   E. None of the above

7. Which of the following methods can be used to turn an SCR off?
   - A. Short the gate to V_{CC}.
   - B. Increase the voltage above the overvoltage limit.
   - C. Disconnect the capacitor resistor filtering system.
   - D. Reverse-bias the gate.
   - E. None of the above

Unit

C

Integrated Circuits

C-1: Op-Amp Theory
C-2: Op-Amp Amplifiers I
C-3: Op-Amp Amplifiers II
C-4: Op-Amp Amplifiers III
C-5: Nonlinear Op-Amp Circuits
C-6: 555 Integrated Circuit
C-7: AM and FM Modulation
C-8: Video Monitoring Systems

C-1

Op-Amp Theory

UNIT OBJECTIVE: Upon completion of this instructional unit, the student will be able to demonstrate a knowledge of integrated circuits and the op-amp circuit.

SPECIFIC OBJECTIVES: Upon completion of this assignment, the student(s) will be able to demonstrate a knowledge of:

- the basic theory of the 741 op-amp
- the construction of an op-amp

TERMS

Differential input voltage: This voltage is the difference between the voltage on the inputs of an op- amp.

Input offset voltage: The differential input voltage necessary to bring the output back to zero volts. The output will shift off zero as a result of the internal transistors not matching exactly.

Common mode gain: The gain of an op-amp when the input signal is the same on both inputs. Noise is usually equal on both inputs; therefore, a better op-amp will have a low common mode gain.

MAKING AN OP-AMP

The op-amp, or operational amplifier, is a commonly used integrated circuit. The circuit was originally designed as a high gain amplifier to perform mathematical computations. It was later made into an integrated circuit (IC).

The first step in making an integrated circuit and an op-amp is to prepare the semiconductor. ***The preparation of the semiconductor involves chemical processes which your study of chemistry will help you understand.*** An integrated circuit starts as a bar of silicon crystal about 6 inches in diameter. The bar is sliced into thin wafers about 5 mils thick.

The next step is to create either the N-type or P-type material, which involves adding the impurities. Different methods are used to add the impurities or dope the silicon. One method involves placing the silicon wafer in a chamber, removing the air, and firing the ions at the silicon that will impregnate it. Another method involves putting the silicon into an oven and blowing a hot gas mixture of ions at the silicon crystal. The oven method requires that a mask be put over the silicon so that the gas only affects the correct areas. In the vacuum method, although a mask is used, an ion gun is used to shoot the ions at the correct places on the silicon.

Finally, oxygen is blown across the face of the semiconductor material which oxidizes it, forming silicon dioxide or glass. This seals off the surface and prepares for the next step.

Different areas of glass are then etched away, and more doping is done in the cleared areas. This process will set up the different areas with the N-type and P-type material. Metal is then deposited on the various collectors, bases, and emitters. The leads for the device are welded to the metal deposited on the collectors, bases, and emitters. Metal is also deposited on the device to provide connection between points.

The complete circuit in an IC is all on one piece of silicon. A circuit built on one piece of silicon is called a monolithic IC. The one piece of silicon helps to match the transistors and diodes, which is important to the op-amp.

Designers prefer to have only active devices in an integrated circuit. They can add resistors, if it is necessary, and occasionally a small capacitor. They never try to add any inductance, since any coil would be too big for an integrated circuit package.

The size of an IC is usually stated according to the number of transistors in the chip. There is a wide variation in the number of transistors that designers put in ICs. An SSI (small-scale integration) will have less than 12 transistors in the chip. An MSI (medium-scale integration) will have from 12 to 100 transistors in a chip, and an LSI (large-scale integration) will have more than 100 transistors. A category has been made for extra large chips called VLSI (very large-scale integration). Some ICs have millions of transistors in them.

Building circuits that are to go inside an IC involves different considerations than for a circuit on a printed circuit board. Using direct coupling instead of capacitive coupling results in a better IC. The differential amplifier is a circuit design that is ideal for integrated circuits. This circuit is a direct coupled amplifier. The differential amplifier is used as the input circuitry for many integrated circuits.

The circuit in figure 1 shows a differential amplifier circuit. The two inputs, V_1 and V are the base inputs of the two input transistors. The output can be taken from either collector. In most circuits it is taken from Q_2, as shown.

Both of the transistors are closely matched in characteristics. Matching is easy for a circuit designer when the whole circuit is on one piece of silicon. Because the two transistors are matched, there will be close to zero volts on the output when the inputs have equal voltages on them.

This circuit has an output only when there is a difference in voltage on the two inputs. If the V_2 input has 2 V on it and the V_1 input has 2.001 V, then the difference in voltage is 0.001 V or 1 mV. If the gain of the op-amp is 1,000, then the output voltage will be 1 V. The output is controlled by the difference between the voltages on the inputs. The actual voltage on the inputs is not amplified, just the difference.

Notice formula 1. It shows the relationship between the input voltages and the output voltage. Multiplication is indicated by a dot between the letter *A* (which stands for the gain) and the difference between V_1 and V_2, which is in parentheses. If we had used an X for multiplication, you could be confused into thinking the X was another term in the equation.

$$V_{out} = (V_1 - V_2) \cdot A \qquad \textit{formula 1}$$

When you have the opportunity to build an op-amp circuit, remember that the inputs are the base inputs of the transistors. This means they must have a dc path to ground. If the base input leads have capacitors in series with no resistance to ground, there will be no current flow for the base emitter junctions and the circuit will not work.

Another new item is shown in figure 1. Look at the negative voltage source labeled V_{EE} and feeding the emitter. The op-amp normally requires a dual supply for operation. In future assignments, you will learn how to surround the op-amp with one supply that appears to be two supplies. With the dual supply, the output (when there is no input) is centered between the two supplies at zero volts.

The differential amplifier shown in figure 1 drives a push-pull class B circuit. This push-pull circuit can provide an output that is close to the full power supply range. If the power supplies driving the op-amp are each 9 V, then the peak-to-peak output voltage will approach 18 V.

The schematic symbol in figure 2 is used for an op-amp and an amplifier. The op-amp is an amplifier, but sometimes a triangle is used for an amplifier that is not an op-amp. A square is used instead of a triangle in circuits that perform a processing operation, such as a voltage regulator.

It is important to always show the polarity of the input leads on the schematic of an op-amp. The output amplitude is a function of the difference between the inputs, but the phase is a function of the individual leads. The input leads are not interchangeable. You must have the right signal inputs going in with the correct phase. The signal on the plus lead is in phase with the output, and the signal on the minus input is 180° out of phase with the output. The op-amp can be drawn with the plus and minus switched to make it easier to show the other connections. The voltage source leads are not usually shown on a schematic. It is assumed that anyone capable of understanding the schematic will know that the op-amp has to have voltage sources connected to it.

Ideally, when there is no signal input to the op-amp, the output will be at zero. No op-amp is perfect, and if the circuit requires that the op-amp output be at zero when there is no input, then the voltages on the inputs will have to be adjusted. The voltage that must be placed on the input to bring the output to zero is called the *input offset voltage*. You will find this parameter listed as a maximum voltage in the information from the manufacturer.

The *differential gain* is the gain that we are normally concerned with. This is the gain of the op-amp or the signal input which is the difference voltage compared with the output voltage.

Another important parameter is the common mode gain. The *common mode gain* is the gain of a signal or voltage that is on both inputs equally. When a voltage is on both inputs equally, there is no difference voltage. Usually, the only voltage that is on both inputs equally is noise. The lower the common mode gain, the better the op-amp is. The *common mode reject ratio,* which is usually written *CMRR*, is the ratio of the differential gain to the common mode gain. This parameter is often expressed in decibels. Since you will study decibels in more detail in a later assignment so we have not given the CMRR in formula 2 in decibels.

$$\mathrm{CMRR} = \frac{A}{A_{cm}}$$ *formula 2*

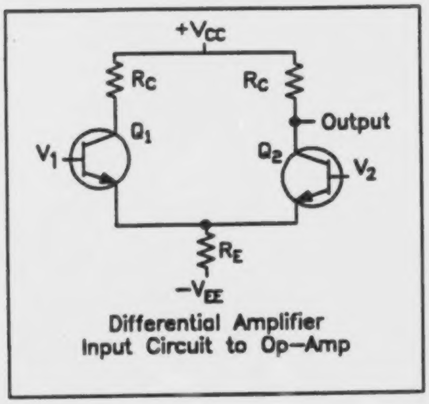
+Vcc
Rc
Rc
Output
Q1
Q2
V1
V2
RE
-VEE
Differential Amplifier
Input Circuit to Op-Amp

Figure 1

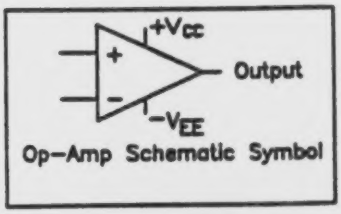
+
−
+Vcc
Output
-VEE
Op-Amp Schematic Symbol

Figure 2

CHARACTERISTICS OF AN OP-AMP

Fairchild Semiconductor introduced the first op-amp, which they labeled the µA709. Although this device was very successful, many improvements were added, and the new version was labeled the µA741. Other manufacturers have copied the basic design and labled their op-amps in a manner similar to the Fairchild device. For example, Motorola labels theirs the MC1741.

The commercial grade 741, which is called the 741c, has an input impedance of 2 MΩ, an output impedance of 75 Ω, and a differential voltage gain of 100,000. The ideal amplifier, or an amplifier approaching perfection, would have a very high input impedance, a low output impedance, and a high gain. For these parameters, the 741c appears to be the ideal amplifier.

This very high gain of 100,000 is too high for normal use of an amplifier. It will cause problems with feedback and oscillations. Thus, additional circuitry is needed to stabilize the op-amp.

The 741 has a 30 pF capacitor that provides negative feedback to help stabilize the device. As the frequency that is being amplified increases, the reactance of the capacitor will go down, and more signal is fed back, causing a reduction in gain. This capacitor will cause the gain to drop by 20 dB for every decade, or 10 times the frequency. A loss of 20 dB is the same as dividing the voltage by 10 to come up with the new voltage. If the frequency is 12 kHz with a voltage gain of 50, then the voltage gain would be 5 at a frequency of 120 kHz.

Remember the RC time constant? When a capacitor is being charged through a resistor, a certain time is required to charge or discharge the capacitor. This is known as the RC time constant, and it is found by multiplying the resistance times the capacitance.

The feedback capacitor inside the op-amp is limited by this RC time constant and can only charge and discharge up to a certain speed. The RC time constants in the op-amp limit the charging time. The *slew rate* is the parameter that describes the rate of charge and discharge for this capacitor in terms of the output signal. The 741c has a slew rate of 0.5 V/µs. This means the output cannot increase or decrease any faster than 0.5 V for each microsecond. If the voltage must go from zero to 3 V for the peak of a sine wave in less than 6 µs, it will not do it. The sine wave will begin to look like a sawtooth wave as the slew rate distortion holds the rate of change. Since the output is limited in the rate at which it can change, this will limit the frequency that is available on the output. A higher frequency can be on the output by reducing the output voltage. Remember that the slew rate is concerned with the rate of change of the voltage. A lower voltage on the output results in a shorter distance that we have to change the voltage, so the rate of change will be less. Formula 3 can be used to determine the maximum frequency that the op-amp can amplify without distorting the signal.

$$f_{max} = \frac{S_R}{2\pi V_P} \qquad \textit{formula 3}$$

We can use formula 3 if we know the slew rate (S_R) and the peak voltage (V_P). According to this formula, the 741c, with a slew rate of 0.5 V/µs divided by 2π times a peak voltage of 6 V, will be able to amplify 13.2 kHz with no slew rate distortion. When you are working this formula, remember to use the 0.5 V/µs as it is written.

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This capacitor in the 741 will also reduce the gain of the 741c to unity gain at 1 MHz. Unity gain means the output signal will be at the same voltage as the input signal. This reduction in gain is a result of the negative feedback and is a progressive change.

The low output impedance of the 741 does not allow it to drive a low impedance load if the current requirements exceed its specifications. The 741 is limited to a maximum short circuit current of 25 mA. If the load has too low an impedance, then the maximum voltage will be limited by the output current available.

OTHER AMPLIFIER ICs

The basic 741 has been copied and modified to provide specialized integrated circuits for other purposes. It is common in the industry to use the term *chips* for integrated circuits. This basic structure of the differential amplifier and the push-pull output is used in many specialized amplifier chips. Some chips with two audio amplifiers inside the package are used for audio preamp circuitry in stereo amplifiers. Some chips have been designed with four amplifiers in one package. Many specialized op-amps are used for motor control feedback and in robotics. Designers will change the internal capacitor for different slew rates and replace the transistor input with JFETs for a higher input impedance. Much higher frequencies can be achieved for use in high-frequency radio systems.

A common application for chips that use some of the features of the op-amp is the voltage regulator. You will study negative feedback in the next assignment, which will help you understand why the basic op-amp circuit is so useful.

EXERCISE: Read each question carefully, and take your time. Use your notebook paper or scrap paper to solve the problems. Round off your answer to the three most significant digits.

1. Approximately what percentage of integrated circuits include an inductor in their circuitry?
   A. 0.5%
   B. 1.0%
   C. 5%
   D. 10%
   E. None of the above

2. What is the relationship between the frequency and the gain of an op-amp?
   A. The gain is not affected by the frequency.
   B. When the frequency gets high enough, the gain will suddenly drop down to unity.
   C. The gain of the circuit is progressively reduced as the frequency is increased.
   D. The higher the frequency, the higher the gain.
   E. None of the above

3. What material is formed when oxygen is blown on a silicon wafer?
   A. Impurities are added, resulting in N-type or P-type material.

B. The oxygen increases the conductivity of the surface.
C. A layer of glass is formed on the surface.
D. The impurities are burned off, reducing the doping at the surface.
E. None of the above

4. If an op-amp with 4.7 V on V_1 and 4.6 V on V_2 has a voltage gain of 100, what will the output voltage be?
A. 100 V
B. 50 V
C. 12 V
D. 10 V
E. None of the above

5. Which one of the following terms would represent a chip that could store over a million bits of information?
A. MSI
B. LSI
C. SMI
D. VLSI
E. None of the above

6. If the dual power supplies when added together equal 24 V, what is the maximum peak-to-peak voltage that the output of an op-amp can approach?
A. 6 V
B. 12 V
C. 24 V
D. 36 V
E. None of the above

7. A differential input of 1 mV results in 0.5 V output and the same input fed in to both inputs as a common mode signal will result in an output of 5 mV. What is the CMRR?
A. 500
B. 250
C. 100
D. 10
E. None of the above

8. With a peak voltage of 4 V, what is the maximum frequency that a 741c op-amp can amplify without slew rate distortion?
A. 5.7 kHz
B. 10 kHz
C. 20 kHz
D. 27.3 kHz
E. None of the above

C-2

Op-Amp Amplifiers I

UNIT OBJECTIVE: Upon completion of this instructional unit, the student will be able to demonstrate a knowledge of integrated circuits and the op-amp circuit.

SPECIFIC OBJECTIVES: Upon completion of this assignment, the student(s) will be able to demonstrate a knowledge of:

- negative feedback circuitry on the op-amp
- how negative feedback affects the circuit parameters

TERMS

Open loop voltage gain: The gain of the op-amp without the feedback circuitry.

Closed loop voltage gain: The actual gain of the circuit as a result of the negative feedback reducing the gain.

NEGATIVE FEEDBACK

The negative feedback concept has become one of the most important concepts in electronics. Negative feedback has a strong influence on distortion, impedance, offset voltages, and gain. With negative feedback, the gain is a function of the value of resistors instead of the parameters of the active components. ***Your studies in mathematics will help you understand the concept of negative feedback, since it makes more sense when you look at it mathematically.***

The very high gain of the op-amps results in negative feedback circuits which are very stable. The gain of the op-amps can be easily set with a high degree of accuracy. Negative feedback takes part of the output voltage and feeds it back to the input. To be negative feedback, the signal must go to an input that is out of phase with the output.

Figure 1 shows one of the common circuits for setting up negative feedback using an op-amp. This circuit is called a noninverting voltage feedback amplifier. The voltage divider, consisting of R_1 and R_2, feeds back a portion of the output voltage to the inverting input. Remember that the inverting input is V_2. There is a minus sign to show which input is the inverting input on the op-amp.

Figure 1 includes the formula for the amount of feedback that is sent back to the input. This amount is labeled *B*. The formula for B is the same formula you studied for voltage dividers.

If R_1 is 9 kΩ and R_2 is 1 kΩ, what would the voltage gain of the op-amp circuit be? Using the formula for B, we find the ratio or the feedback B to be 1/10 or 0.1.

The second formula in figure 1 is the formula for the voltage gain, which is simply inverting B. This tells us that the gain of this circuit is based on the values of resistors R_1 and R_2.

To find the gain in our example, we invert B, which is 0.1, to get a gain of 10. Notice that the open-loop gain of the op-amp was not considered in our calculations. The only determining factor is the resistance of the voltage divider off the output of the op-amp.

These formulas are accurate because of the high open-loop gain of the op-amp. To keep the accuracy and stability high, it is important not to use resistors with too large a value for R_1 and R_2. The voltage divider is in parallel with the input impedance. Since the input impedance is so high, 2 MΩ, it will have little effect on the gain when resistors R_1 and R_2 are much lower in resistance. Try to keep the sum of resistors R_1 and R_2 below 200 kΩ to maintain this accuracy.

Remember that the output of the 741 op-amp can deliver only about 25 mA of current. The resistive divider R_1 and R_2 must have enough resistance to avoid taking a significant amount of that current. If the sum of the resistors is between 30 and 60 kΩ, then this would be a good compromise. By combining the two formulas in figure 1, we are able to arrive at formula 1.

$$A_{cl} = \frac{R_1}{R_2} + 1 \qquad \textit{formula 1}$$

In formula 1, the term A_{cl} stands for the closed loop (*cl*) voltage gain (*A*). The closed loop gain is the gain including the negative feedback loop. Open loop gain is the gain of the device itself including any feedback networks. For the 741c op-amp, the gain is normally figured at 100,000. The actual gain of the 741c will be between 75,000 and 150,000.

The actual gain of the op-amp is not important. What is important is that the gain of the op-amp is much higher than the closed loop gain we want from our circuit. By solving formula 1 for R_1, we come up with formula 2, which will be helpful in designing simple op-amp circuits.

$$R_1 = R_2(A_{cl} - 1) \qquad \textit{formula 2}$$

If you use the circuit that we have in figure 1, formula 2 will give you the ability to design op-amp circuits for a specific gain. Remember the guidelines for the sum of resistors R_1 and R_2, and you can just pick a value for resistor R_2. Then plug the gain and the value you have for resistor R_2 into formula 2 and solve for the value of resistor R_1.

If we wanted a gain of 15 using the circuit in figure 1, what values should resistors R_1 and R_2 be? Let's pick a value of 2.7 kΩ for resistor R_2. Formula 2 will then give us 14 times the 2.7 kΩ, or 37.8 kΩ, for resistor R_1. This is a relatively easy circuit to design. We have not shown the power supply connections to the op-amp, but you need to remember that two supplies are needed. A negative supply is usually labeled V_{EE}, and the positive supply is labeled V_{CC}.

INVERTING AMPLIFIER

When a technician wants an easy op-amp circuit to provide some gain in a circuit, the circuit in figure 2 is probably the easiest. Notice that the source voltage and Z_{out} in figure 2 represent the

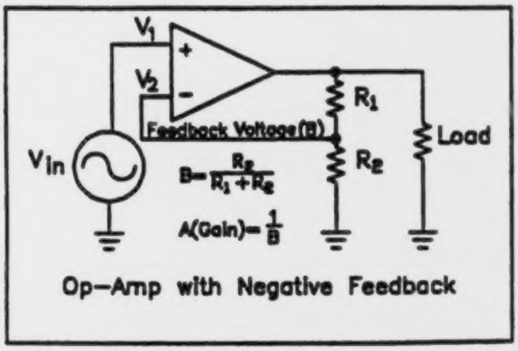

V1
V2
+
−
R1
Feedback Voltage(B)
Load
Vin
R2
B = R2/(R1+R2)
A(Gain) = 1/B
Op-Amp with Negative Feedback

Figure 1

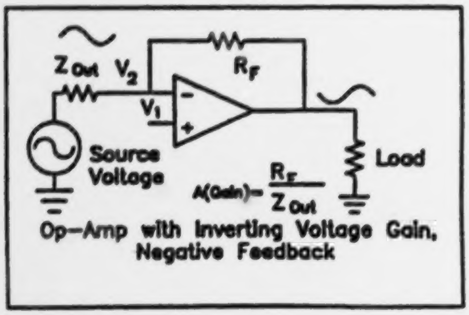

Z Out
V2
RF
V1
−
+
Source Voltage
Load
A(Gain) = RF/Z Out
Op-Amp with Inverting Voltage Gain, Negative Feedback

Figure 2

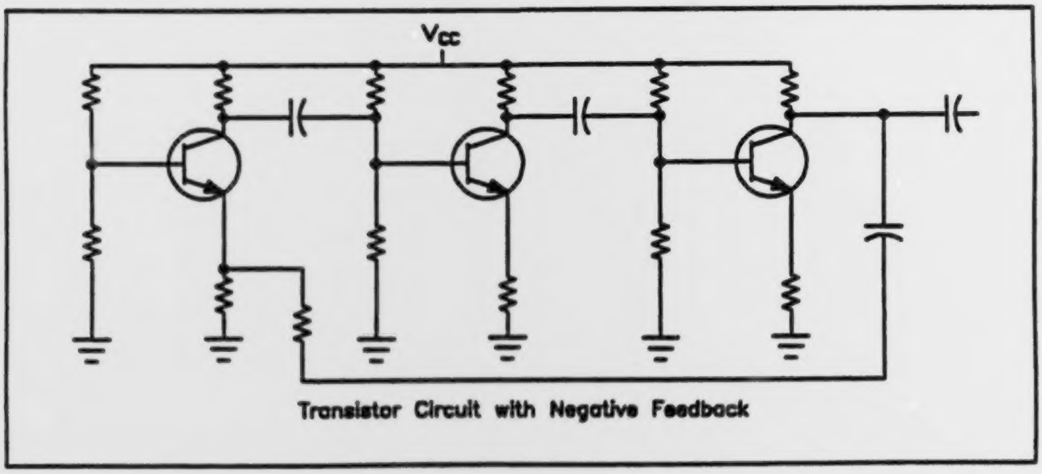

Vcc
Transistor Circuit with Negative Feedback

Figure 3

Thevenin equivalent of a signal source. The feedback network consists of the resistor R_F and the Z_{out} from the source. We have not connected anything to V_1 to remind you that you will have to do something with that input. If you use a dual supply, then V_1 should be grounded.

Note how both the input signal and the feedback come into the inverting input in this circuit. The output from this circuit will be 180° out of phase with the input signal.

The voltage gain of the circuit, as shown by formula 3 and the formula below the circuit (fig. 2), is equal to the resistor R_F divided by the output impedance of the source.

$A_{cl} = R_F/Z_{out}$ *formula 3*

THE EFFECT OF NEGATIVE FEEDBACK

Figures 1 and 2 have a different response to the negative feedback. Both of these circuits will have a change in their gain, input and output impedance, distortion, and offset voltage levels as a result of negative feedback. The amount and direction of the change is different for the circuits.

The change in figure 1 can be determined from the mathematical term (1+AB). This means the change is 1 plus the open loop gain times the feedback factor. This term (1+AB) is called the *desensitivity factor*. If we have a circuit gain or closed loop gain of 10 for figure 1, then the value of B will be 0.1. The value of A is 100,000. This means that (1+AB) equals 10,001. This will increase the input impedance of the circuit in figure 1 by 10,001 times the open loop input impedance of 2 MΩ.

Figure 2 will change based on the mathematical term (1+A). So (1+A), with A equal to 100,000, is 100,001. This results in a very large amount of change for the parameters of the circuit.

The circuit in figure 2 will show a reduction in its input impedance by the value of R_F divided by the factor (1+A). A 10 kΩ resistor for R_F will give a closed loop input impedance of 0.1 Ω. This low input impedance results in what is called a virtual ground. When troubleshooting the circuit in figure 2, it is important to remember this low impedance. The voltage at this point will be very low or nonexistent. The circuit will appear to have no input. This could cause you to look in the wrong place when trying to find the failure. This low input impedance, or virtual ground, is not an actual ground since it may have a dc potential and will not sink very much current.

Both figures 1 and 2 will decrease their output impedance by the desensitivity factor. This will result in an output impedance of less than 1 Ω. The distortion and offset voltages will also both be decreased by the desensitivity factors.

FREQUENCY RESPONSE

The frequency response of a circuit is often considered the bandwidth of the circuit. The ***bandwidth*** of a circuit is defined as the range of frequencies that are between the upper and lower cutoff frequencies. The cutoff frequencies are the high and low frequency points where the circuit gain drops by 3 dB. For the op-amp circuits in figures 1 and 2, the lower cutoff frequency is zero or dc. The upper cutoff frequency will be changed by the negative feedback.

For a small signal, the op-amp, under open loop conditions, will roll off the gain 20 dB for every ten times the increase in frequency or 20 dB per decade. The open loop cutoff frequency for the 741c is 10 Hz. When we add negative feedback to the op-amp circuit and reduce the gain, the frequency response becomes flat at that gain level until it reaches the open loop frequency at that gain level. For example, if our negative feedback is giving us a gain of 100, then the frequency response will show a gain of 100 up to a frequency of approximately 10 kHz. At 10 kHz the open loop gain is also 100. As the frequency increases past 10 kHz under closed loop conditions, the gain falls off at 20 dB per decade just as it would under open loop conditions.

Another way to look at it is, when negative feedback is added, the new cutoff frequency or bandwidth becomes the 10 Hz multiplied by (1+AB) or (1+A). We can multiply the gain of the circuit by the bandwidth and get the gain bandwidth product. This figure is often listed in the manufacturer's literature. The gain bandwidth product will be the same for any op-amp from the open loop condition to unity gain.

For the 741c, the open loop gain is 100,000, which when multiplied by 10 Hz gives 1 MHz. If we take the unity gain and multiply it by the bandwidth, which is 1 MHz, we get 1 MHz again. The 1 MHz is the unity gain for the 741c op-amp. The manufacturer may list the unity gain frequency, which is the same as the gain bandwidth product.

Remember that the negative feedback does not change the slew rate of the op-amp. A large signal may run into the slew rate limit before it gets to cutoff. The rate of change on the output is limited by the slew rate. The slew rate for the 741c is 0.5 V/µs. This means the voltage on the output cannot change any faster than 0.5 V every microsecond.

Negative feedback is essential for the op-amp amplifiers you have studied. Negative feedback will work on any amplifier, but it is more useful when the amplifier has a very high gain like an op-amp.

Figure 3 shows a typical three-stage transistor amplifier. This amplifier will not have enough gain to use the formulas that we have just given you. Notice how part of the output in figure 3 is taken from the collector of the third stage and fed back to the emitter of the first stage. Remember that the phase changes from the base to the collector and is the same between the base and the emitter. If we examine the phase by starting at the base of the first stage and label the phase at that point as *plus* (+), then the collector of the first stage is 180° different from the base, or *minus* (-). It helps to use plus and minus signs to determine what the phase is in a circuit when the two points you are comparing are far apart. The minus phase on the collector of the first stage will also be minus on the base of the second stage and plus again on the collector of the second stage. This plus will then appear on the base of the third stage, which results in a minus on the collector of the third stage. This minus will then appear on the emitter of the first stage as it is fed back. Since the emitter and the base of a transistor are in phase, the signal that is fed back is 180° out of phase with the signal on the base.

The circuit in figure 4 is similar to the one in figure 1 except that all the output is fed back to the input. This results in unity gain with a very high input impedance and a low output impedance. This circuit is valuable for matching a high output impedance with a low input impedance.

CONCLUSION

Negative feedback is very important in electronic circuitry. The op-amp circuits you have studied would be of little value without the stabilizing effect of negative feedback. Remember that negative feedback always feeds some or all the output back to the inverting input, or the input that is out of phase with the output. The negative feedback always reduces the gain of the circuit, improves any distortion that is generated within the feedback loop, and changes the input and output impedances. Positive feedback will increase the gain of the circuit, and if there is enough positive feedback, the circuit will oscillate.

EXERCISE: Read each question carefully, and take your time. Use your notebook paper or scrap paper to solve the problems. Round off your answer to the three most significant digits.

1. In figure 5, R_F is 18 kΩ. What is the gain of this op-amp circuit?
   A. 20.2
   B. 9.25
   C. 18.0
   D. 6.3
   E. None of the above

2. In figure 5, if there is a 3 mV rms signal input to the circuit and the same 18 kΩ resistor for R_F, how much signal would you see on pin 2 of the op-amp?
   A. 3 mV rms
   B. 2 mV rms
   C. 1 mV rms
   D. 0 mV rms
   E. None of the above

3. In the circuit in figure 6, what should the value of R_1 be for a gain of 12, if R_2 is a 1 kΩ resistor?
   A. 10 kΩ
   B. 6 kΩ
   C. 22 kΩ
   D. 11 kΩ
   E. None of the above

4. In figure 6, R_1 is equal to 51 kΩ and R_2 is equal to 1.8 kΩ. What is the closed loop gain?
   A. 28.3
   B. 29.3
   C. 49.2
   D. 37.4
   E. None of the above

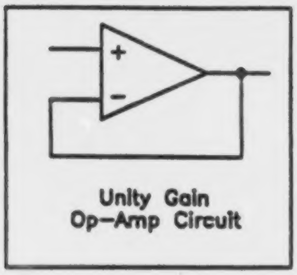

+
−
Unity Gain
Op-Amp Circuit

Figure 4

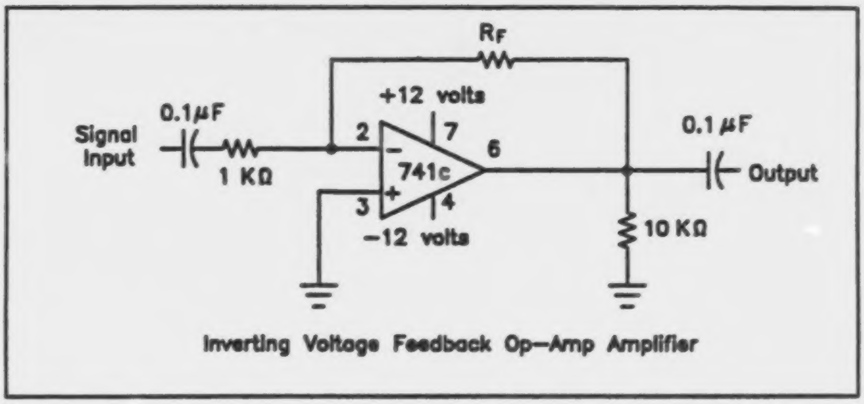

R_F
+12 volts
Signal Input
0.1µF
1 KΩ
2
7
6
741c
3
4
−12 volts
0.1 µF
Output
10 KΩ
Inverting Voltage Feedback Op-Amp Amplifier

Figure 5

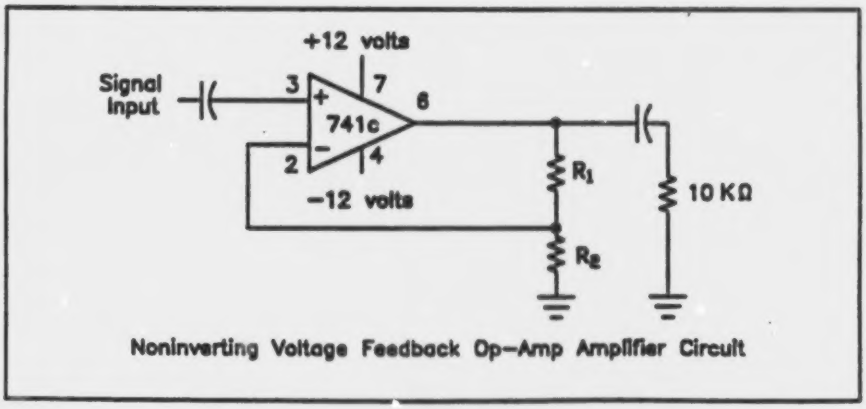

+12 volts
Signal Input
3
7
6
741c
2
4
−12 volts
R_1
R_2
10 KΩ
Noninverting Voltage Feedback Op-Amp Amplifier Circuit

Figure 6

5. If all of the output is connected back to the input on a 741c, what is the upper cutoff frequency?
   A. 250 kHz
   B. 500 kHz
   C. 1 MHz
   D. 2 MHz
   E. None of the above

6. What is the slew rate of a 741c op-amp?
   A. 5 V/µs
   B. 12
   C. 0.5 V/µs
   D. 36
   E. None of the above

7. In figure 6, what is the closed loop input impedance of the 741c op-amp, if the open loop gain "A" is 100,000, and R_1 and R_2 give a closed loop gain of 6? The open loop input impedance of the op-amp is 2 MΩ.
   A. 16,000 MΩ
   B. 33,000 MΩ
   C. 47,000 MΩ
   D. 870 MΩ
   E. None of the above

C-3

Op-Amp Amplifiers II

UNIT OBJECTIVE: Upon completion of this instructional unit, the student will be able to demonstrate a knowledge of integrated circuits and the op-amp circuit.

SPECIFIC OBJECTIVES: Upon completion of this assignment, the student(s) will be able to demonstrate a knowledge of:

- using a single supply with op-amp circuitry
- adding additional circuitry inside the feedback loop

TERMS

Bandwidth: The range of frequencies between the points where the amplitude of the signal drops 3 dB.

Feedback loop: The circuitry that feeds the output signal back to the input of the amplifier.

NONINVERTING VOLTAGE OP-AMP CIRCUITRY

Manufacturers prefer to build circuits with only one power supply instead of the two needed for the op-amp. You have studied dual supplies first because the single supply appears to the op-amp like a dual supply.

The op-amp circuitry in figure 1 shows the single supply circuitry. Notice the voltage divider network on the positive or noninverting input to the op-amp. This voltage divider network consists of the two resistors, each labeled R_{in}. This is the primary feature of the single supply circuitry. We have put a voltage equal to half of V_{CC} on the inputs to the op-amp. This will cause the output to have a dc bias equal to half of V_{CC} as well. The result is that all of the voltages around the op-amp give the appearance to the op-amp of a dual supply. Each supply appears to be equal to half of V_{CC}.

By adding some voltages to the circuit and using your knowledge of algebra, you will be able to understand how this concept works. Let's make V_{CC} equal to 12 V. This will put 6 V at the positive or noninverting input. The two inputs will be equal, which will put 6 V at the negative or inverting input. There will also be 6 V on the output.

Now, if we look at it like the op-amp does, the ground connection will be 6 V below the input and output. This is what would happen if we had two 6 V supplies feeding V_{CC} and V_{EE}. According to the op-amp, there is no difference between dual 6 V supplies and a single 12 V supply.

We could bias the positive or noninverting input at something other than half of V_{CC}. This would then appear to the op-amp as unequal dual power supplies.

Each of the two resistors R_{in} that make up this voltage divider are in parallel with the input impedance of the op-amp. The input impedance of the 741c op-amp is 2 MΩ. This is generally much larger than the resistors used for the voltage divider. The parallel combination of these resistors and the input impedance of the op-amp will show the lower impedance of the resistors as dominant. If we put 100 kΩ resistors in each of the R_{in} spots, then the input impedance of the circuit will be 50 kΩ.

We do not have to use a voltage divider to provide a bias voltage for single supply. The bias voltage can be obtained from another circuit, such as the collector of the transistor feeding the signal to it. When another circuit is used to supply the dc bias for the op-amp, a capacitor is not needed to block the dc.

Building the op-amp on one piece of silicon in an integrated circuit results in closely matched components. However, they are not perfectly matched. The slight variations in the two transistors in the input circuitry will result in a voltage on the output which is off from the nominal. This is called the *offset voltage*. Also, variations in current in the input circuitry will cause the output to be offset, or offset voltage. The offset voltage is a dc parameter, usually measured under a no signal condition, that is normally amplified with the signal.

Notice capacitor C_3 in figure 1. The addition of capacitor C_3 to the circuit in series with resistor R_2 will block the dc from going to ground and feed all the dc feedback voltage, or offset voltage, back to the input. This will result in unity gain for the offset voltage. If the signal voltage is amplified with a voltage gain of 10, then this circuitry will have reduced the offset voltage by 10.

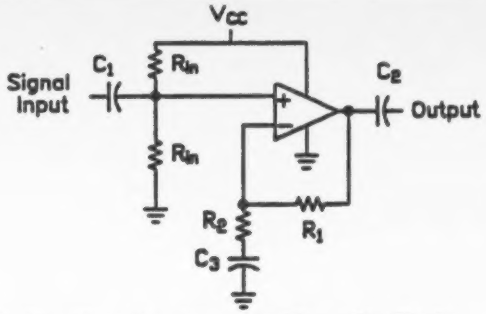
The capacitor that is picked for the C_3 location and for the other locations should have a low reactance to the signal. If the capacitor reactance is too high, it will be adding effective resistance to the fixed resistors which control the gain. Also, when a capacitor has some influence in the gain of the circuit, the frequency response will not be flat. Variations in frequency can cause the gain to change with the frequency.

Briefly, the single supply noninverting op-amp circuit, which is set up for single supply, will have the noninverting input at half of V_{CC}. The voltage divider on the noninverting input will lower the input impedance. If the circuit needs a low offset and will not be amplifying dc, then the capacitor in series with the feedback resistance can be added. The offset voltage is reduced by making the gain for the offset voltage equal to one, or unity gain. This gives the circuit's lower cutoff frequency a value above zero.

INVERTING VOLTAGE AMPLIFIER

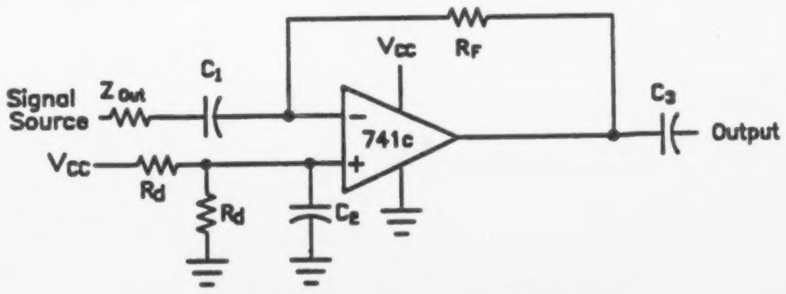
The inverting voltage amplifier, shown in figure 2, has been set up for single supply using the same basic rules. The positive or noninverting input is biased at half of V_{CC}. The two resistors that form the voltage divider to bias the positive input are labeled R_d and are equal.

The capacitor C_2, shown from the positive input to ground, is there to put the positive or noninverting input at ac ground. This will remove any ripple that might be in the power supply. The capacitors C_1 and C_3 are used to provide the dc isolation from the circuitry connected to the input and output of the op-amp.


Vcc
Signal Input
C1
Rin
Rin
C2
Output
+
−
R2
R1
C3

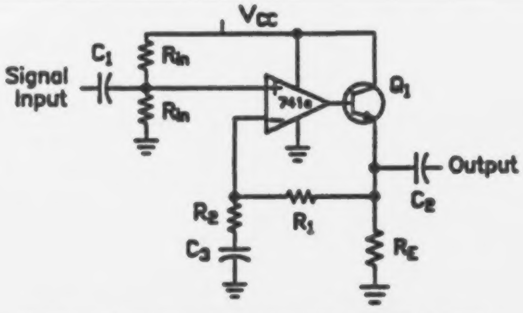
Noninverting Op-Amp Amplifier with Single Supply and Reduced Output Offset Voltage

Figure 1


RF
Vcc
C1
Signal Source
Z out
C3
Output
−
741c
+
Vcc
Rd
Rd
C2

Inverting Voltage Amplifier with Single Supply

Figure 2


Vcc
C1
Rin
Signal Input
Rin
741c
Q1
Output
C2
R2
R1
C3
RE

Noninverting Op-Amp Amplifier with Single Supply and Emitter Follower in the Feedback Loop

Figure 3

The gain of the op-amp circuit is still the value of R_F divided by the output impedance of the voltage source. The reactance of the input and output capacitors to the signal will change the frequency response of this circuit. The capacitors should have a high enough value to give a low reactance to any expected frequency.

HIGHER LEVELS OF OUTPUT CURRENT

The 741c, like most general purpose op-amps, does not supply very much current. The way to increase the available current is to add some transistor circuitry and include this additional circuitry in the feedback loop. The 741c can only supply about 25 mA of current. The very low output impedance does not guarantee an unlimited amount of current. The circuit in figure 3 shows the transistor Q_1 providing that additional current to the load.

When you studied emitter followers, you learned that this circuit can supply a lot of current and has a low output impedance. Since the transistor is in the feedback loop, the output impedance will be even lower. The output impedance of this circuit is equal to the output impedance of the emitter follower divided by the factor (1+AB). This is close to the same output impedance that the op-amp would have without the transistor on its output.

Remember that the output of the op-amp will have a voltage equal to V_{CC} divided by two. This is the same voltage at which you would normally bias an emitter follower. Since the base of the emitter follower is connected to the output of the op-amp, the bias voltage on the output of the op-amp will provide the bias voltage for the emitter follower.

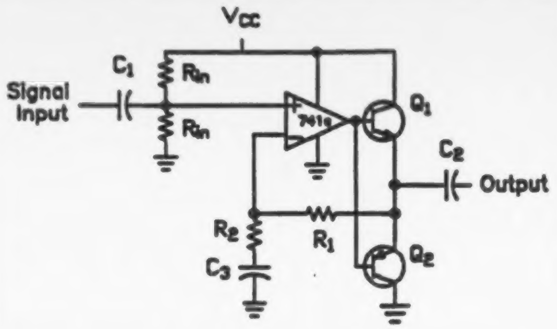
The amount of current that the transistor can deliver depends on the beta of the transistor and the 25 mA that the op-amp can deliver. If a darlington transistor is used, the amount of current available becomes rather large. The emitter follower circuit will only allow current to flow in one direction.

To have current flowing in both directions, a push-pull amplifier can be added to the circuitry and included in the feedback loop with the op-amp. The negative feedback will set up the bias and reduce crossover distortion. Notice in figure 4 how the feedback path can come from the output of the circuit back to the inverting input. The crossover distortion is distortion that is produced within the feedback loop and would be reduced by the factor (1+AB). The bias on the push-pull output transistors would be controlled by the negative feedback.

In figure 5 we have added the emitter follower circuit to the inverting voltage amplifier. The feedback is picked up from the emitter on this circuit just like the noninverting voltage amplifier. We can find the gain for this circuit using the same formulas as for the circuit without an emitter follower. There is no loss between the op-amp and the transistor because of the effect of the negative feedback. The negative feedback also sets the bias for the transistor and reduces all internally generated distortion. We can include other circuits within the feedback loop and take advantage of the negative feedback.

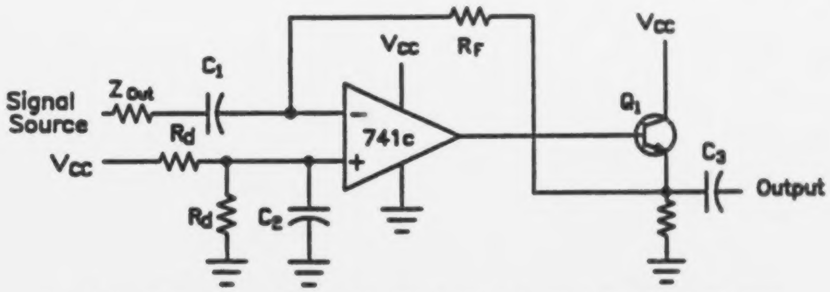
SUMMARY

You should remember the basic concepts that apply to designing a single supply op-amp circuit and adding additional circuits within the feedback loop. To design a single supply op-amp circuit,


Vcc
C1
Rin
Signal Input
Rin
741c
Q1
C2
Output
R2
R1
C3
Q2

Noninverting Op-Amp Amplifier with Single Supply and Class B Push Pull Output within the Feedback Loop

Figure 4


RF
Vcc
Vcc
C1
Signal Source
Zout
Rd
Vcc
741c
Q1
C3
Output
Rd
C2

Inverting Voltage Amplifier with Single Supply and Emitter Follower in Feedback Loop

Figure 5

always bias the positive or noninverting input at half of V_{CC} unless another voltage is appropriate for the circuit. The negative feedback must be brought back to the negative or inverting input. Remember that the feedback goes back to the input with the minus sign for negative feedback. If you have additional circuitry within the feedback loop, pick up the signal from the output at a point that is in phase with the output of the op-amp.

The negative feedback will reduce the internally generated distortion, and the gain of the circuit will be a function of the voltage divider network in the feedback loop. The output impedance becomes lower by dividing the device's output impedance by (1+AB) or (1+A), and the input impedance will change depending on the type of circuit that is used.

You must isolate different dc voltages with capacitors. If the op-amp circuit is being fed by a circuit output that has a suitable dc bias on it, then no additional biasing network will be needed.

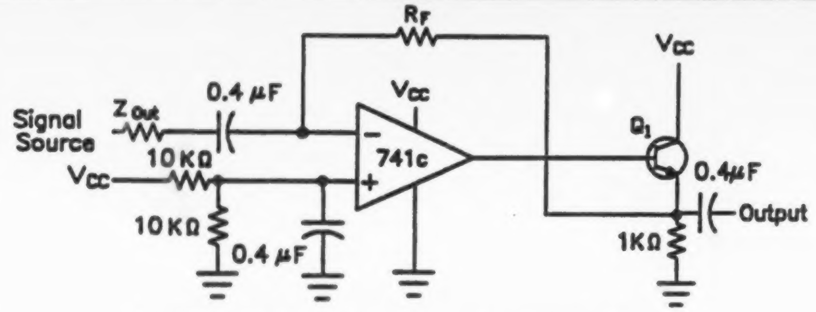
You can add a capacitor in series with R_2 on the noninverting circuit to reduce the dc gain to unity gain. This will reduce the offset voltage problem. The inverting voltage amplifier should have a capacitor on the inverting input to put that point at ac ground. This will reduce any ripple from the power supply that might be amplified.

EXERCISE: Read each question carefully, and take your time. Use your notebook paper or scrap paper to solve the problems. Round off your answer to the three most significant digits.

1. In figure 6, if the emitter follower has an output impedance of 30 Ω without the negative feedback and the open loop gain is 100,000 , what is the output impedance with the negative feedback?
   A. 5 Ω
   B. 0.3 mΩ
   C. 0.02 μΩ
   D. 1.3 mΩ
   E. None of the above

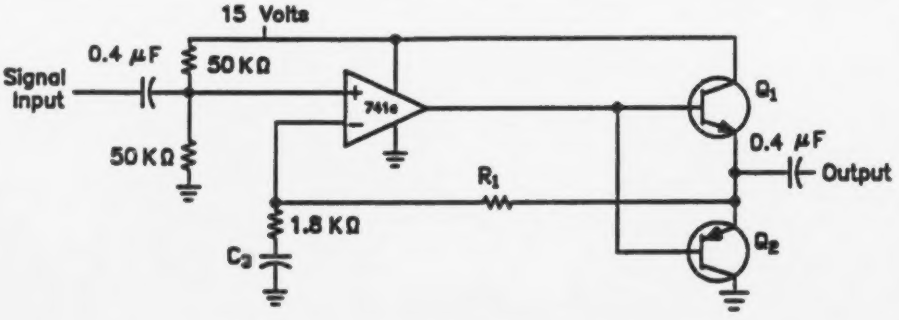
2. If the Z_{out} is 600 Ω and the gain is 20 in figure 6, what is the resistance value of R_F?
   A. 120 kΩ
   B. 30 Ω
   C. 12 kΩ
   D. 8.7 kΩ
   E. None of the above

3. If there is a 15 mV source driving the circuit in figure 6 and you used a scope probe to observe the signal on the input between the capacitor and the op amp, approximately how much voltage would you see?
   A. 15 mV
   B. 7.5 mV
   C. 5 mV
   D. 2.5 mV


Rf
Vcc
0.4 µF
Vcc
Signal Source
Zout
10 KΩ
Vcc
741c
Q1
0.4µF
Output
10 KΩ
0.4 µF
1KΩ

Inverting Voltage Amplifier with Single Supply

Figure 6


15 Volts
0.4 µF
50 KΩ
Signal Input
741c
Q1
0.4 µF
Output
50 KΩ
R1
1.8 KΩ
C3
Q2

Noninverting Op-Amp Amplifier with Single Supply

Figure 7

E. None of the above

4. In figure 7, what is the ac output compliance or the maximum voltage swing that is available on the output?
   A. 15 V
   B. 12 V
   C. 6 V
   D. 10 V
   E. None of the above

5. In figure 7, if the capacitor C_3 has 1 kΩ of reactance and R_1 is 6.8 kΩ, what is the gain of the circuit?
   A. 5.7
   B. 3.8
   C. 4.8
   D. 3.4
   E. None of the above

6. In figure 7, what is the input impedance?
   A. 50 kΩ
   B. 25 kΩ
   C. 12.5 kΩ
   D. 100 kΩ
   E. None of the above

7. In figure 7, what value should resistor R_1 be for a gain of 25?
   A. 86 kΩ
   B. 14.9 kΩ
   C. 45.0 kΩ
   D. 43 kΩ
   E. None of the above

C-4

Op-Amp Amplifiers III

UNIT OBJECTIVE: Upon completion of this instructional unit, the student will be able to demonstrate a knowledge of integrated circuits and the op-amp circuit.

SPECIFIC OBJECTIVES: Upon completion of this assignment, the student(s) will be able to demonstrate a knowledge of:

- other important op-amp circuits
- how to troubleshoot unfamiliar op-amp circuits

TERMS

Buffer circuit: The buffer circuit will act to separate circuits and isolate a circuit to allow it to remain stable.

DAC: The digital analog converter is a circuit that takes a digital or computer signal and converts it to a linear signal.

NEW CIRCUITS

In this assignment, we are going to present some new circuits using the op-amp. They are all common circuits, although they are often drawn a little different than what we have done. ***You may have noticed already how much your mathematics courses help you to understand these circuits. In mathematics, you learned how to take an expression and combine it with other expressions for a more complex mathematical statement. You can do the same thing here by looking at each of these circuits as a collection of building blocks.***

In previous assignments, you have learned about negative feedback, single supply, and adding additional circuitry to supply more current than the op-amp was capable of handling. Each of these concepts can be used in a circuit to accomplish something different.

MIXER

The circuit shown in figure 1 is the inverting op-amp amplifier. The difference between the amplifier you studied in the last assignment and this one is that this one has four inputs instead of just one. If all four inputs are in phase, the circuit will add the inputs. This amplifier is often used as an audio mixer. It is useful for mixing microphone audio before sending it to the final amplifier recording equipment. The potentiometer on each input will set the gain for that input, and the potentiometer in the R_F position will set the gain for the amplifier.

For example, if resistor R_5, which is R_F, is set at 1 kΩ and resistor R_1 at 500 Ω, then the input into resistor R_1 or input #1 would be amplified by a factor of 2, or the 1 kΩ of R_F divided by the 500 Ω of R_1. A 1 V input into input #1 would result in 2 V on the output. If the gain from input #2 resulted in 3 V on the output, then the total output would be the 2 V plus the 3 V for a total of 5 V. This is assuming that the signals are either dc or in phase.

Another application of this circuit is adding various voltage levels from a digital circuit. This circuit will have fixed resistors in all the positions for mixing the incoming signals. Each of the resistors is different to give different gain levels. The gain required will depend on the position of the input.

VOLTAGE SOURCE

In a manufacturing environment, the product that is produced has to meet many specifications. If one of the specifications is a certain voltage and many different inspectors will be testing for that voltage, then it can be important to verify that the meters used to test for that voltage are accurate.

The calibrated voltage source shown in figure 2 can be used to calibrate and verify other test equipment. This voltage source can be used to calibrate computerized testing equipment that is often used to test the circuitry of the product during the manufacturing process. The calibrated voltage is helpful in checking the computer's accuracy at testing the products' circuits.

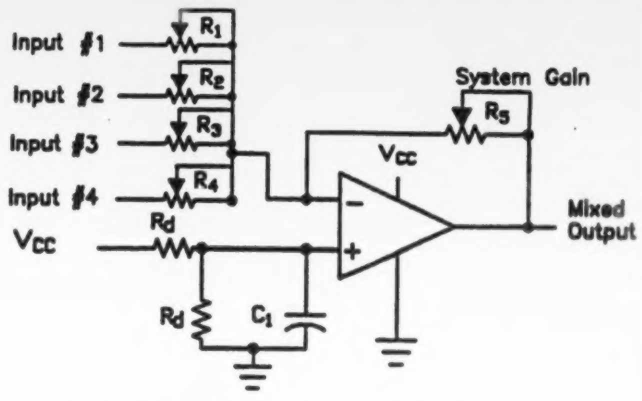
We have shown the circuit with an 18 V power source. This was done because 9 V batteries are easy to obtain. Two 9 V batteries will do an excellent job of suppling the voltage necessary for this circuit. If you will remember the noninverting voltage amplifier from the last assignment, you will notice that this circuit is a standard noninverting voltage amplifier. The signal that is being amplified is the voltage from the zener diode. Since the input impedance to the op-amp is high, the zener will see no variation in current. Remember that the zener has internal resistance or impedance, and will have slight voltage variations with changes in the current that passes through it.

The potentiometer R_2 is used to adjust the calibrated source. A good voltmeter, which is designated as the standard, would be used to set the voltage on the source. Then the other voltmeters can be compared with the standard.

Capacitor C_1 will provide a path around R_1 for any variation in voltage or ac signals that may be present. The capacitor will appear as a short to the voltage variation and be directed back to the input. The variation will see a unity gain compared with the gain of the reference voltage. The 5 V zener that was used will not change its voltage with changes in temperature.

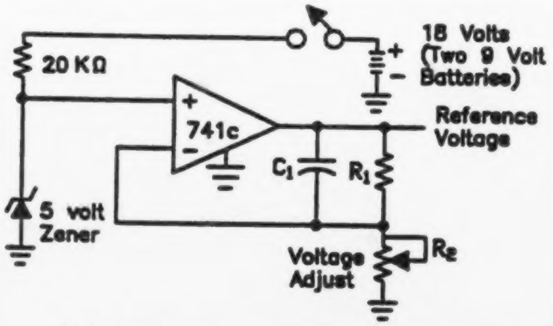
DIFFERENTIAL AMPLIFIER

In figure 3, the four resistors that are shown in the bridge arrangement is a bridge sensor. The resistor with the circle around it would be the one that changes value with changes in the temperature or volume or whatever is being measured. The sensor may be a strain gauge or


Input #1
R1
Input #2
R2
Input #3
R3
Input #4
R4
Rd
Vcc
System Gain
R5
Vcc
Mixed Output
Rd
C1

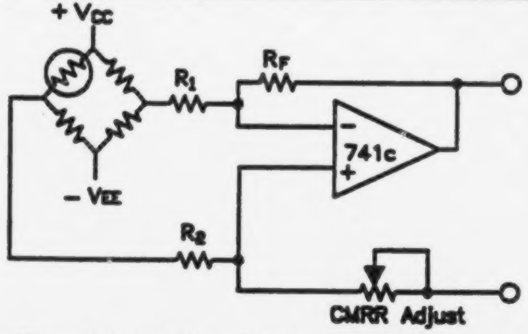
Mixed Amplifier Suitable for Audio Mixing

Figure 1


20 KΩ
18 Volts (Two 9 Volt Batteries)
741c
Reference Voltage
C1
R1
5 volt Zener
Voltage Adjust
R2

Voltage Source for Calibration Purposes

Figure 2


+ Vcc
R1
RF
741c
− VEE
R2
CMRR Adjust

Differential Amplifier with Remote Sensor Input

Figure 3

temperature gauge on some remote piece of equipment. As this resistor changes value, the bridge becomes unbalanced.

The op-amp circuit in figure 3 is used to amplify the unbalanced signal from the sensors. The resistance bridge, which we show as the input to the op-amp, is a common method for setting up a sensor. The dual voltage sources will give a voltage input across the inputs to the op-amp at all times. The op-amp must only amplify a difference voltage, or the difference between the voltages coming into the two inputs. With 3 V on one input and 2.95 V on the other input, there will be a 0.05 V difference between the two inputs. If the amplifier has a gain of 100, then the output voltage should be 5 V.

The common mode reject ratio needs to be high for this type of circuit. The CMRR adjust will allow the technician that installs this circuit to null out any common mode gain that may be present. Sometimes this circuit will include two additional op-amps that will be set up with unity gain on each of the inputs to provide isolation from the sensor circuitry. These sensors can often pick up noise and ac hum from other electronic equipment or wiring that may be in the area. The common mode rejection should result in no amplification of this noise coming from the sensor circuitry, since the noise will have equal voltage levels on both of the inputs to the op-amp.

FILTERS

Excellent filters can be made using op-amps. In previous assignments you learned about passive filters with coils and capacitors. An active filter has an active device in it such as an op-amp, while a passive filter will only have passive components such as capacitors, coils, and resistors. Designers prefer not to use coils if they can avoid them because coils are bulky and expensive.

The circuit in figure 4 is a low-pass active filter. When you examine this circuit, notice that the circuit has resistors R_3 and R_4 which are part of the negative feedback path. These two resistors indicate that this circuit is a noninverting voltage amplifier. Capacitor C_2 provides positive feedback in the circuit. Remember that the capacitor will have a different reactance to different frequencies.

Notice the differences between figure 4 and figure 5. Resistors 1 and 2 in figure 4 have been replaced by capacitors, and the capacitor in figure 4 is now a resistor in figure 5. The circuit in figure 5 is a high-pass filter, which means that it will pass frequencies above its cutoff frequency and reject those below. The cutoff frequency is the point where the amplitude of the signal drops 3 dB.

Two other popular types of filters are the band pass and the band reject. We can make a band-pass filter by putting a low-pass filter in series with a high-pass filter. If the cutoff frequency of the low-pass is 1,200 Hz and the cutoff frequency of the high-pass is 800 Hz, the band of frequencies that the filter will pass is from 800 to 1,200 Hz. This would be a band-pass filter.

If we switch the cutoff frequency with the type of filter, we can make a band-reject filter in the same way. The mathematics necessary to design a filter or determine the values needed for the individual components is very complex. Today, most filters are designed using computers to handle all of the computations.

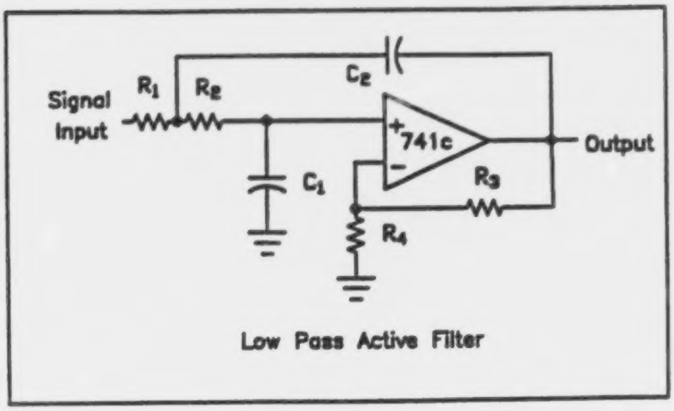

Signal Input
R1
R2
C2
C1
741c
Output
R3
R4
Low Pass Active Filter

Figure 4

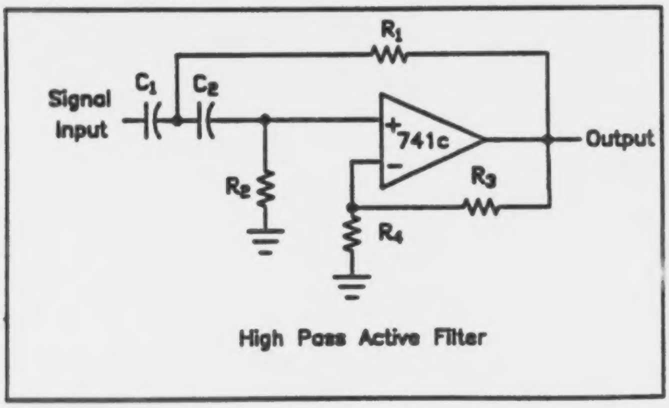

R1
Signal Input
C1
C2
741c
Output
R2
R3
R4
High Pass Active Filter

Figure 5

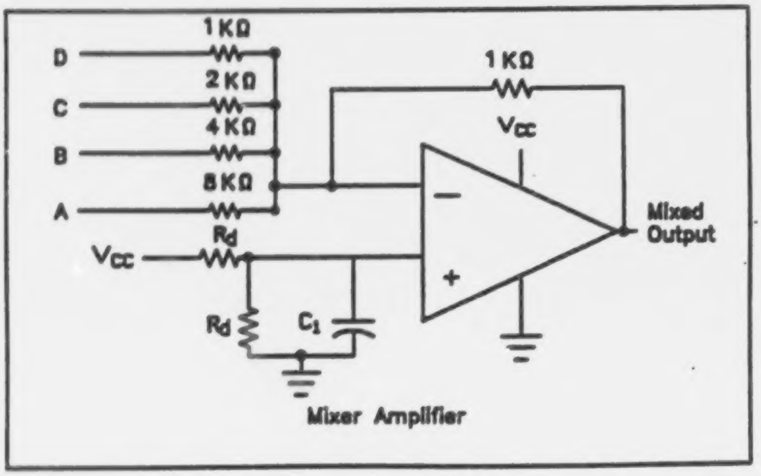

1 KΩ
D
2 KΩ
C
4 KΩ
B
8 KΩ
A
1 KΩ
Vcc
Mixed Output
Rd
Vcc
Rd
C1
Mixer Amplifier

Figure 6

You should be able to recognize and identify which type of filter you have in a circuit. Notice the position of the capacitors and resistors in the two filters in figures 4 and 5. One way to remember which one is which, is to remember that the reactance of a capacitor goes down as the frequency goes up. The filter with the capacitor shown across the input, or with one end grounded, would take the higher frequencies to ground. This would then be a low-pass filter. The filter with the capacitors in series with the signal would show a lower impedance as the frequency increased, which would be a high-pass filter.

Both of these filters are two-pole or second-order filters. The number of poles or orders is determined by the terms in the mathematical expressions used to design the filters. A single-order filter in figure 4 would not have R_2 or C_2. The higher the order or the more poles in a filter, the sharper the cutoff frequency. A single-pole filter will reduce the signal by 20 dB per decade, a two-pole by 40 dB per decade, and a three-pole by 60 dB per decade.

EXERCISE: Read each question carefully, and take your time. Use your notebook paper or scrap paper to solve the problems. Round off your answer to the three most significant digits.

1. If we combined a high-pass filter with a cutoff of 25 kHz and a low-pass filter with a cutoff of 24 kHz, what kind of filter would we have?
   A. Band pass
   B. High pass
   C. Band reject
   D. Low pass
   E. None of the above

2. How much attenuation of the signal, per decade, will a two-pole, low-pass filter have?
   A. 20 dB
   B. 30 dB
   C. 40 dB
   D. 50 dB
   E. None of the above

3. How much gain does the circuit in figure 6 have from input A only?
   A. 0.75
   B. 0.5
   C. 0.25
   D. 0.125
   E. None of the above

4. If there is 5 V on all inputs in figure 6, what is the output voltage?
   A. 9.375 V
   B. 15.25 V
   C. 6.025 V

D. 12.325 V
E. None of the above

5. What is the voltage on the output in figure 7 if the gate voltage on the JFET has resulted in an R_{DS} of 1 kΩ and there is 10 mV on the input?
   A. 1.38 V
   B. 690 mV
   C. 427 mV
   D. 275 mV
   E. None of the above

6. In figure 7, what is the input impedance of the circuit?
   A. 20 kΩ
   B. 10 kΩ
   C. 5 kΩ
   D. 2.5 kΩ
   E. None of the above

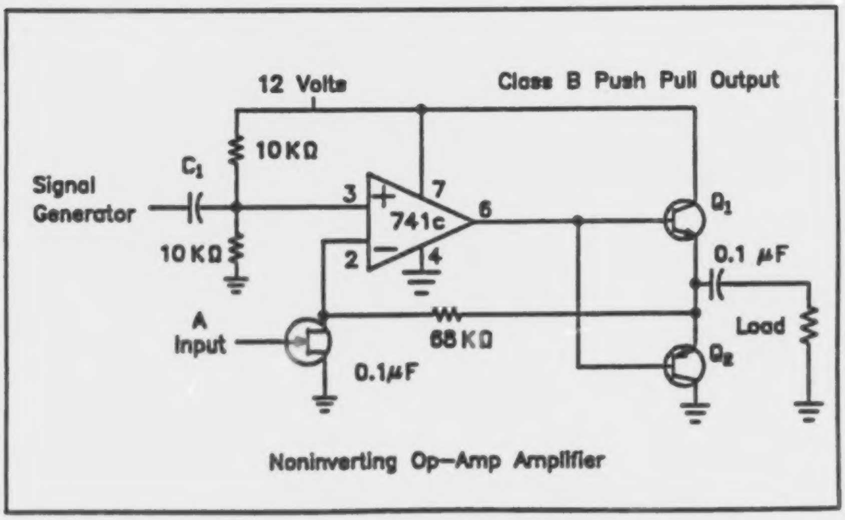

12 Volts
Class B Push Pull Output
10 KΩ
C_1
Signal Generator
3
7
741c
6
Q_1
10 KΩ
2
4
0.1 µF
A
Input
68 KΩ
Load
0.1µF
Q_2
Noninverting Op–Amp Amplifier

Figure 7

C-5

Nonlinear Op-Amp Circuits

UNIT OBJECTIVE: Upon completion of this instructional unit, the student will be able to demonstrate a knowledge of integrated circuits and the op-amp circuit.

SPECIFIC OBJECTIVES: Upon completion of this assignment, the student(s) will be able to demonstrate a knowledge of:

- what comparators and Schmitt triggers are
- how the nonlinear comparator and Schmitt trigger circuits work

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TERMS

Nonlinear: A nonlinear circuit will change the shape of an input signal.

Comparator: A comparator circuit is a switching circuit. It will switch when the input voltage passes a reference voltage.

Schmitt trigger: The Schmitt trigger is a comparator that has different switching points when going from high to low and low to high. These different switching points result in hysteresis.

LINEAR VS. NONLINEAR

The op-amp type of circuit is very useful for nonlinear circuits. The high gain of the op-amp circuit lends itself to many designs. A nonlinear circuit is different from a linear circuit in the way it processes the signal. ***You studied this in computer mathematics.*** A linear circuit will change the voltage or current of a signal input, but will not change the shape of the signal. A nonlinear circuit will react to a signal by putting out some other voltage or signal that does not always look like the input signal.

A comparator is a circuit that is similar to an op-amp with internal changes to speed up its switching. The comparator can suddenly switch its output from 0 V to 5 V, when a steadily increasing voltage on the input passes a reference voltage point on the other input. This switching will result in the output signal not having the shape or appearance of the input signal.

The transistor amplifier, which you have studied in the past, will keep the shape of a signal input, and increase the voltage of the signal on the output. This is a linear function.

COMPARATOR

The comparator in figure 1 uses a single supply, which results in a simpler and more useful circuit. Notice that there is no negative feedback in this circuit. Without the negative feedback to reduce the gain of this circuit, the gain will be approximately 100,000. This circuit can be made with either an op-amp or a comparator integrated circuit designed for this purpose. Either input can be biased or used as the signal input. The choice of input will determine the polarity of the output.

In figure 1, we have biased the inverting input. If we assume a V_{CC} of 12 V and equal resistors biasing the input, then the bias voltage will be 6 V. If the voltage on the input is 10 V, then the difference voltage will be a plus 4 V.

The high gain will drive the output into saturation. The output will go positive as far as it can. It can only go to 12 V since that is the maximum voltage available. Actually, the output voltage will not go all the way to 12 V. It may be 1 V or 2 V short of that depending on the device used for the comparator.

Now we can examine it by watching what happens as we let the voltage on the input rise. We can start with a voltage input of 0 V, and watch the action of the circuit. Remember, we have 6 V on the negative input. As the input voltage rises to 5 V, the negative voltage on the input becomes smaller. The voltage on the input is the difference between the two inputs. At 5 V on the positive input or signal input, there is a minus 1 V on the input of the circuit. Putting this in a formula may help to understand what is happening. Formula 1 shows what the output is with the two inputs v_1 and v_2.

$$V_{out} = A(v_1 - v_2) \qquad \textit{formula 1}$$

The term v_1 is the noninverting (+) input, and v_2 is the inverting (-) input. The term A is the gain of 100,000. With a gain this high, if the difference between v_1 and v_2 is more then 0.12 mV, the output will be in saturation. The input voltage will have to increase up to a point that is within 0.12 mV of the 6 V reference voltage before the output will start to change. Then the output will completely switch during the 0.12 mV change in the input. All voltages on the positive input above the 6 V reference voltage will hold the output high.

If the 6 V reference voltage is on the positive input and we start a signal from 0 V on the negative or inverting input, then everything will happen in reverse. The output will start high, and as the voltage on the negative input is increased past the reference voltage, the output will switch low. If the voltages on the two inputs result in a larger voltage for input v_2 in formula 1, then the output will be low or negative. The output will go to ground potential if the circuit has a single supply.

Op-amps that are designed for linear circuits, like the 741c, do not switch fast enough for some circuits. Remember, the slew rate will limit the rate of change on the output. The slew rate will keep the 741c from changing any faster then 0.5 V/µs. Although there are faster op-amps than the 741c, all of the op-amps designed for linear use have an internal capacitor to roll off the higher frequencies and eliminate oscillation. This internal capacitor will limit the switching action on the output or the slew rate.

Switching circuits do not have a problem with oscillation. The switching circuits are either in the off condition or in full saturation which will eliminate oscillation. They have no need for the internal capacitor.

Manufacturers have designed comparators that are op-amps without the internal capacitor and with a different output circuit. The 741c and other similar op-amps have a class B push-pull output. The comparators have an open collector output.

ADDITIONAL COMPARATORS

A simplified version of a comparator circuit is shown in figure 2. Notice the output, which is the collector of the output transistor. The collector does not have a collector resistor, which is why it is called an open collector. The collector is the output of the circuit, and there is no internal collector resistor or other connection to the collector.

The input to this circuit is the basic differential amplifier that you are familiar with. This circuitry will switch in less than a microsecond while the 741c, with a 5 V output and a slew rate of 0.5v/µs, will take 10 microseconds.

To complete the circuit with an open collector, a pull-up resistor is added externally to the collector output and to a voltage source. When the transistor is off or not conducting the voltage on the output will equal the voltage source. When the transistor is conducting, the voltage drop across the pull-up resistor will result in close to 0 V on the output.

The value of the pull-up resistor becomes a compromise between speed and supplying sufficient current to the load. A transistor will switch faster if less current is passing through it. A higher value pull-up resistor to limit the current will allow the transistor to switch faster. This higher value of pull-up resistor will leave less current for the load. The pull-up resistor should be small enough to provide adequate current to the load only.

The class B push-pull output circuit used in linear op-amps has another problem. The outputs cannot be wired in parallel. If two op-amps with push-pull outputs are wired in parallel, the output voltage will not be correct when one is high and the other is low. The problem is that the current will go from the output that is high to the output that is low and be taken to ground. The impedance of the two outputs will result in a voltage divider that will give a voltage on the output at approximately half of V_{CC}. Although the outputs are usually protected from the high level of current that this condition causes, the output voltage will not make sense to digital circuitry.

WINDOW COMPARATOR

Remember that complex circuits are made from simple circuits. The circuit in figure 3 is made from two comparator circuits like the one in figure 1. Notice that these two comparators have a common input.

The circuit in figure 3 is called a window comparator. A window comparator is designed to turn on only when the input is within a range of voltages called the *window*. Each of the two comparator circuits has voltage dividers that set the upper and lower limits for the window. The upper limit is set by the top voltage divider using the 10 kΩ and 20 kΩ resistors. This results in a

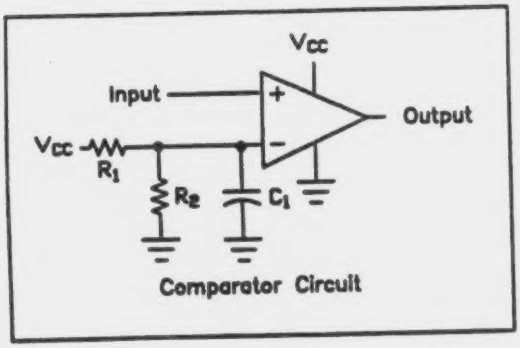

Vcc
Input
Output
Vcc
R1
R2
C1
Comparator Circuit

Figure 1

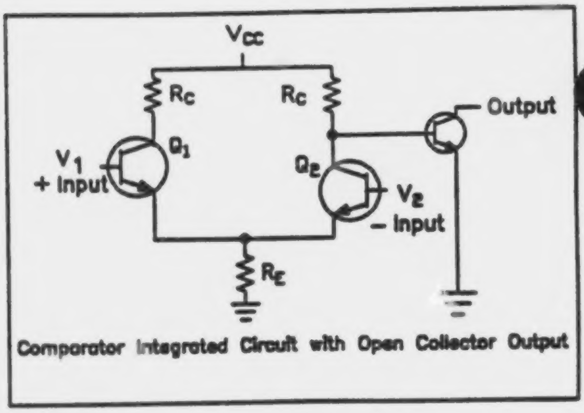

Vcc
Rc
Rc
Output
V1
+ Input
Q1
Q2
V2
− Input
RE
Comparator Integrated Circuit with Open Collector Output

Figure 2

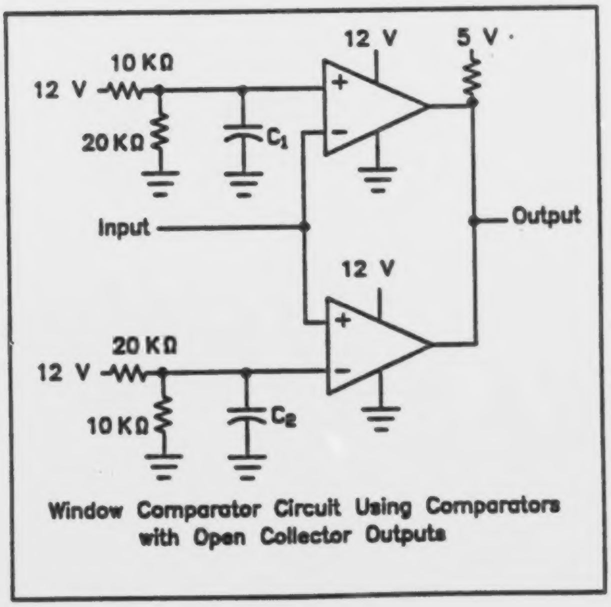

12 V
5 V
10 KΩ
12 V
20 KΩ
C1
Input
Output
12 V
20 KΩ
12 V
10 KΩ
C2
Window Comparator Circuit Using Comparators with Open Collector Outputs

Figure 3

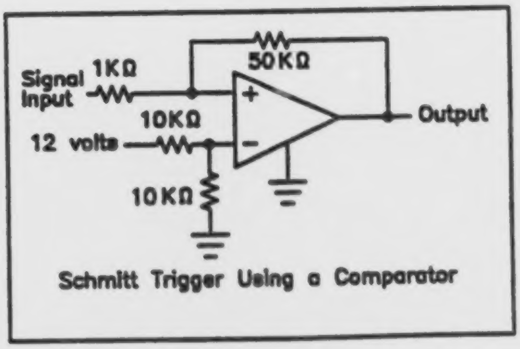

50 KΩ
Signal Input
1 KΩ
10 KΩ
12 volts
Output
10 KΩ
Schmitt Trigger Using a Comparator

Figure 4

voltage of 8 V, which is set on the noninverting or positive input of the top comparator. The bottom voltage divider will set 4 V on the inverting or negative input of that comparator.

Notice that the outputs of the two comparators in this circuit are in parallel. If we used 741c op-amps for this circuit, there would be problems. This circuit requires a comparator and not an op-amp.

Let's examine how the circuit works with some voltages. The top comparator has 8 V on its positive input, and the bottom comparator has 4 V on its negative input. If we start with a low voltage, below 4 V, on the common input to this circuit, the output will be at 0 V. An input voltage of 3 V will result in the lower comparator having a differential input of -1 V. This -1 V input will cause the lower comparator's output to switch low or turn on the transistor with the open collector. This transistor with the open collector will hold the output at 0 V.

The output on the other comparator, or the top comparator, can be either high or low, and the output will remain at 0 V as long as one of the outputs is holding it low by being turned on. The 3 V on the upper comparator is less than the 8 V on the positive input, so the top comparator will be high or its output transistor will be turned off.

To get the output of the circuit to go high, both open collector circuits will have to be high or the transistors turned off. When the voltage on the common input rises above the 4 V reference on the lower comparator, the lower comparator will switch high. This turns off the transistor in the output of the lower comparator. This voltage above 4 V will now put both comparators with their output transistors off. No current flow will result in no voltage drop across the pull-up resistor. The voltage on the output will be equal to the voltage source or 5 V.

As the voltage on the input climbs higher and passes the 8 V reference on the upper comparator, the upper comparator will switch low and drain the current to ground. This will result in the output going back to 0 V. Notice that the only time when both comparators are high is when the voltage is between 4 V and 8 V. Also, we have added two capacitors C_1 and C_2 to provide an ac ground at the reference voltage input.

SCHMITT TRIGGER

The two capacitors C_1 and C_2 in figure 3 will filter the power supply noise, but they will not filter the noise out of the signal. With just a comparator, a noise pulse on the signal can cause the comparator to switch on and off momentarily before the signal reaches the trigger voltage. This extra pulse can look like additional information to a computer and result in errors. The Schmitt trigger was designed to solve this problem. It will switch on and off at different voltages.

The difference in the switching voltages is called *hysteresis* and is created by the positive feedback. Notice that figure 4 looks like an inverting voltage amplifier in which someone got the polarity on the op-amp wrong. This feedback system, which is positive and not negative, will create the spread between the turn-on and turn-off voltages. The voltage divider will set the reference voltage. You can use formula 2 to find the center voltage, or the voltage which is centered between the upper and lower trigger points.

$$V_C = V_r\left(\frac{R_S}{R_F} + 1\right) \qquad \textit{formula 2}$$

In the formula, V_r is the voltage set by the voltage divider, or the reference voltage. In figure 4 the reference voltage is half of the 12 V or 6 V. The formula for the center voltage gives us 1.02 times the reference voltage of 6 V, or 6.12 V for the center voltage.

The 50 kΩ resistor for R_F does not change the voltage from the voltage divider by very much. Formulas 3 and 4 can be used to find the trigger voltages that will cause the Schmitt trigger to switch on and off.

Switch-on voltage: $U = V_C + \frac{R_S}{R_F}(V_S)$ *formula 3*

Switch-off voltage: $U = V_C - \frac{R_S}{R_F}(V_S)$ *formula 4*

The term V_S, in formulas 3 and 4, is the saturation voltage. This is the voltage that the output will go to when the device is turned off. Since digital circuitry requires a high of approximately 5 V, we can use 5 V in formulas 3 and 4. Formula 2 gave a center voltage V_C of 6.12 V. Formula 3 will now give a switch-on voltage of 6.22 V, and formula 4 will give a switch-off voltage of 6.02 V. This 0.2 V spread is often enough for many circuits; however, if more of a spread is desired, we can lower the value of R_F and increase the positive feedback. An R_F of 5 kΩ will give a spread of 4.8 V. This would require over 4.8 V of noise to create a false pulse on the output.

INTEGRATOR

The integrator circuit performs a mathematical operation of integration. This means it will produce an output voltage that is proportional to the mathematical integral of the input. A level dc voltage on the input to this circuit will result in a ramp output. A *ramp output* is a steadily increasing or decreasing voltage.

The integrator circuit is an inverting voltage amplifier with R_F replaced by a capacitor. The ramp is made on the output during the time the capacitor is charging. When the capacitor is fully charged, the output will level off to a flat dc. This circuit can be used to create a sawtooth waveform from a square wave.

DIFFERENTIATOR

The differentiator circuit is the opposite of the integrator. This circuit is made by switching the resistor R_S with a capacitor instead of the resistor R_F. This circuit could be used to produce a square wave from a sawtooth wave.

The circuit is more useful in generating short spikes from square wave inputs. The output from this circuit will generate a spike that goes negative on one side of a square wave input and a positive spike on the other side of the square wave input. These spikes are useful as timing marks for the leading edge or trailing edge of square wave pulses in digital circuits.

EXERCISE: Read each question carefully, and take your time. Use your notebook paper or scrap paper to solve the problems. Round off your answer to the three most significant digits.

1. If you switched the polarity on the op-amp of an inverting voltage amplifier, what would the circuit resemble?
   A. Integrator
   B. Schmitt trigger
   C. Differentiator
   D. A mistake
   E. None of the above

2. What kind of feedback does the Schmitt trigger use to create hysteresis?
   A. Induced
   B. Negative
   C. Actual
   D. Positive
   E. None of the above

3. What is the difference between the turn-on voltage and the turn-off voltage for a Schmitt trigger called?
   A. Hysteresis
   B. Difference voltage
   C. Trigger voltages
   D. Noise pulse
   E. None of the above

4. Which input should be used for the input on a simple comparator if the output must go low when the input signal goes high?
   A. Positive
   B. Either input will work.
   C. A comparator will not invert the output.
   D. Inverting
   E. None of the above

5. The output of an open collector comparator circuit is feeding a circuit that requires 5 V and 3 mA. What size should the pull-up resistor be?
   A. 16.7 kΩ
   B. 4.7 kΩ
   C. 1.7 kΩ
   D. 1.2 kΩ
   E. None of the above

6. If we parallel three open collector output circuits and one is turned on and the other two are turned off, what voltage would there be on the output if the single supply voltage is 12 V?
   - A. 12 V
   - B. 6 V
   - C. 11 V
   - D. 0 V
   - E. None of the above

7. How fast will a 741c op-amp switch 10 V?
   - A. 28 ms
   - B. 20 µs
   - C. 15 µs
   - D. 35 µs
   - E. None of the above

C-6

555 Integrated Circuit

UNIT OBJECTIVE: Upon completion of this instructional unit, the student will be able to demonstrate a knowledge of integrated circuits and the op-amp circuit.

SPECIFIC OBJECTIVES: Upon completion of this assignment, the student(s) will be able to demonstrate a knowledge of:

- how the 555 timer integrated circuit operates
- how to use and troubleshoot circuits using 555 timer chips

TERMS

One shot: A circuit that will put out a controlled pulse when it is triggered. A controlled pulse means that the length and timing of the pulse can be controlled.

Flip-flop: The flip-flop is the basic unit in a computer memory. It is stable in both the high and low condition.

555 TIMER

As we have stated before, complex circuits are made up of simpler circuits. We will be studying some more complex integrated circuits in this assignment. The flip-flop, which is part of the 555 circuit, will be studied in more depth when you start studying digital circuits.

The 555 timer chip is a useful and commonly used circuit. The single 555 timer chip is readily available in an 8-pin integrated circuit package. The 556 is two 555 timers in one package, and the 558 is four timers in one package.

Notice that inside the 555 timer chip are two comparators, one transistor with an open collector, and a box labeled flip-flop. The flip-flop is a basic memory device used in many digital circuits. There are two outputs on the flip-flop. These two outputs are both labeled Q, and one of the Qs has a bar over it. ***Your courses in computer mathematics or Boolean algebra discussed the concept of putting a bar over a reciprocal expression.*** Putting a bar over a letter means it is logically inverted. These two outputs are inverted from one another, which means if one is high the other will be low.

The R, S, and Clear are inputs to the flip-flop. The S stands for set, and the R stands for reset. The R and S inputs are normally low. This means that when the circuit is not receiving an input, the state of the two inputs is low, or the voltage on the inputs is zero or close to it. When the S input receives a high, which is a signal to the S input, the Q output will go high. When the R input receives a high, then the output will go low. Both the R and S inputs cannot receive a high at the same time or the circuit will not operate. When the Clear input receives a high, the Q output will go low. The Clear can override any signal coming into the R and S inputs.

ONE SHOT

In figure 1, if we assume that V_{CC} is 12 V, the high is also 12 V, and the low is 0 V, then it may be easier to understand how the circuit operates. With 12 V for V_{CC}, the voltage divider will supply 4 V to the noninverting or positive input of comparator #1 and 8 V to the negative input of comparator #2. Now let's put the 555 circuit in figure 1 into a circuit called a one shot in figure 2. We still have the 12 V for V_{CC} and 0 V for ground.

This one shot circuit in figure 2 is designed to put out a pulse that is of a specific duration, or a controlled pulse. The pulse duration or length is based on the RC time constant of capacitor C_1 and resistor R_1. The circuit will put out this pulse when it receives a trigger pulse. The trigger pulse will come in pin 2 as shown in the drawing. The pulse must be a negative pulse, and the normal condition for pin 2 must be high. Notice the negative pulse in the drawing beside pin 2.

Look at figure 1 again, and notice that pin 2 of the chip is connected to the negative input of comparator #1. The other input to comparator #1 has 4 V on it. When a trigger pulse is received on pin 2, dropping it below 4 V, the comparator will switch its output high. This high feeds into the R (reset) input of the flip-flop. When the flip-flop receives the high on its R input, it will switch the output, on pin 3 of the chip, high and the Q out will go low, turning off the transistor and opening the current path from the capacitor.

This will result in the capacitor now starting to charge. The capacitor receives the charging current from resistor R_1 which is connected to V_{CC}. Notice in figure 2 that pin 6 is connected to the top of the capacitor along with pin 7 from the transistor. When the capacitor charges up to 8 V, this 8 V will appear on pin 6 and on the positive input of comparator #2. This will cause comparator #2 to switch to a positive output and put a high on the S (set) input to the flip-flop. The high on the S input will switch the flip-flop, causing the output to go low and the Q to go high, turning on the transistor and providing a current path to ground from the capacitor. This open current path will discharge the capacitor.

The momentary trigger pulse or the low on pin 2 is gone. Comparator #1, which is needed to reset the flip-flop to continue with another pulse, is waiting for another trigger input. The output will have gone from a low to a high, and back to a low. The duration of the output pulse, or the time that the output is high, depends on the values of resistor R_1 and capacitor C_1. The one input we have not discussed is pin 4. This input is tied to V_{CC} to avoid clearing the flip-flop at the wrong time.

PULSE GENERATOR

The circuit in figure 3 is figure 2 modified to generate a series of pulses without requiring a trigger for each pulse. Notice, in figure 2, that a negative input pulse into pin 2 is necessary to trigger the circuit. We brought the input to pin 2 around and connected it to the top of the capacitor. A resistor was also added between R_1 and capacitor C_1.

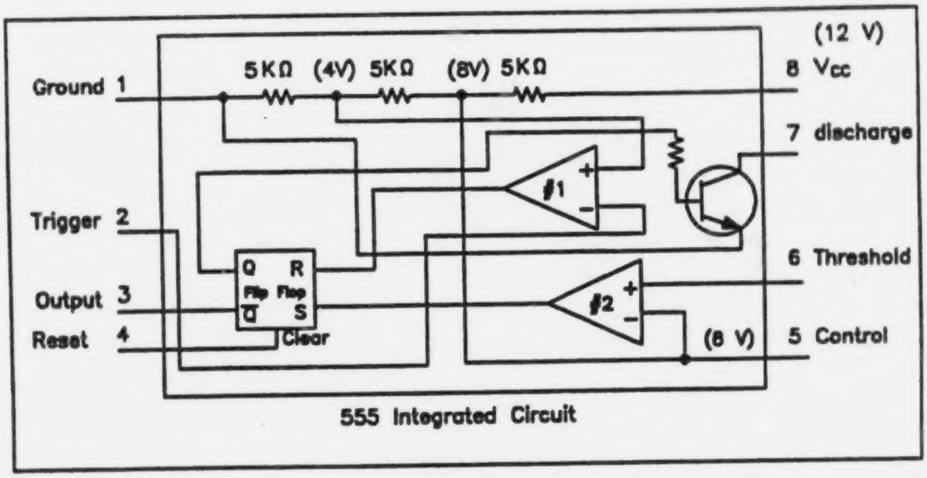

(12 V)
Ground 1
5KΩ
(4V)
5KΩ
(8V)
5KΩ
8 Vcc
7 discharge
#1
Trigger 2
6 Threshold
Q
R
Flip Flop
Output 3
$\overline{Q}$
S
#2
Reset 4
Clear
(8 V)
5 Control
555 Integrated Circuit

Figure 1

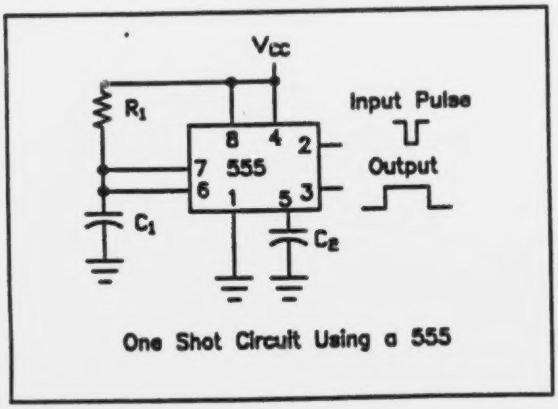

Vcc
R1
8
4
2
Input Pulse
7
555
Output
6
1
5
3
C1
C2
One Shot Circuit Using a 555

Figure 2

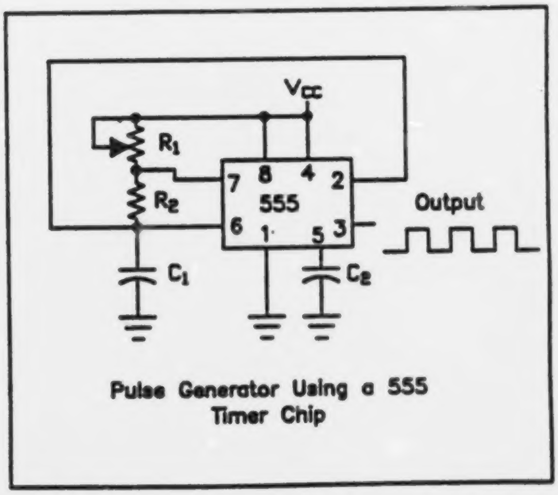

Vcc
R1
7
8
4
2
R2
555
Output
6
1
5
3
C1
C2
Pulse Generator Using a 555 Timer Chip

Figure 3

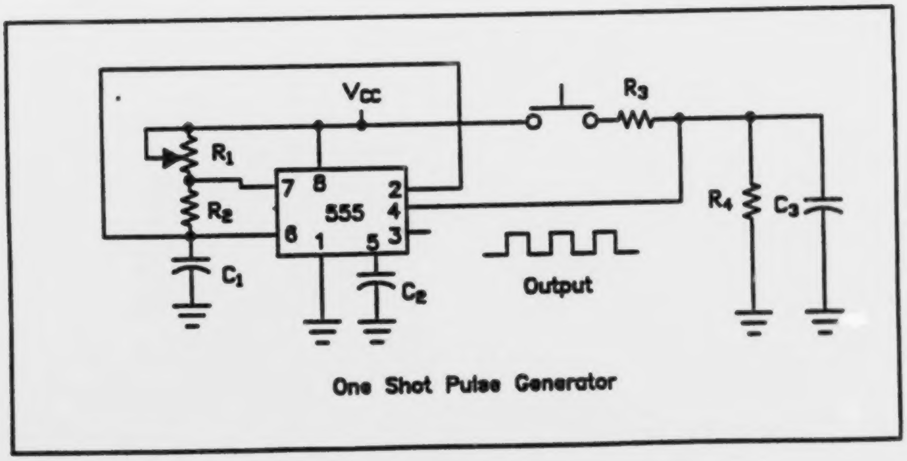

Vcc
R3
R1
7
8
2
R2
555
4
R4
C3
6
1
5
3
C1
C2
Output
One Shot Pulse Generator

Figure 4

When the circuit is first energized, or V_{CC} is applied, the capacitor is in a state of discharge which will put a low on pin 2. The positive input of comparator #1 will have the 4 V from the voltage divider and the low from pin 2 which is connected to the top of the discharged capacitor. This will cause comparator #1 to go high and reset the flip-flop. The reset flip-flop will switch, the Q output will go low, and the output on pin 3 will go high. This high is the start of our first pulse out of pin 3. The low on the Q output will turn off the transistor and open or block the current from flowing away from the capacitor C_1. The capacitor will now start to charge.

The charging current for the capacitor is coming through the two resistors, R_1 and the new resistor we just added. As the capacitor charges, the voltage increases at the top of the capacitor where pin 6 is connected. Pin 6 is also connected to the positive input of comparator #2. The negative input of comparator #2 has the 8 V on it from the internal voltage divider. When the capacitor has charged up to 8 V, comparator #2 will switch to a high on its output and put a high into the set input of the flip-flop. This high on the set input will cause the flip-flop to switch and put a high on the Q output. The output on pin 3 will go low for the completion of the first pulse.

The high on the Q output will turn on the transistor, which will drain the current from the capacitor through the new resistor we added. This resistor will add time to the discharge cycle. This time on the discharge cycle will give a spread between pulses. When the capacitor has discharged down to 4 V, comparator #1 will switch, putting a high on the reset input of the flip-flop. The flip-flop will switch the output high for the second pulse, and the Q output will go low, turning off the transistor and opening the current path that was discharging the capacitor. Now the capacitor will charge again. During the charge cycle of the capacitor, the output is high; and during the discharge cycle of the capacitor, the output is low.

If we change the values of the components that affect the RC time constant for either the charge or discharge cycle, we can change the length of time for the low or high portion of the output pulses. This cycle will continue as long as V_{CC} is connected to the circuit.

ONE SHOT PULSE GENERATOR

The circuit in figure 4 has combined the one shot and the pulse generator. This was done by changing the way pin 4 is connected. Pin 4 is connected to the flip-flop clear input. When the clear goes low, it will put the Q output low and the output at pin 3 high. This input overrides all other inputs. If this clear input is low, the set and reset inputs have no control over the output of the flip-flop.

Now we can start looking at this circuit by assuming that V_{CC} is connected to the circuit and the switch is open. With the switch open, pin 4 will remain low as a result of R_4 being a ground return. Capacitor C_3 will be discharged through resistor R_4. The output from this circuit is then high; and with the Q output low, the transistor is turned off, allowing capacitor C_1 to charge.

Capacitor C_1 will charge up past the 8 V that would have triggered the change before because pin 4 is holding the flip-flop and will not let it switch. Comparator #2 will go high as the voltage on the capacitor passes 8 V, putting a high on the set input of the flip-flop. The flip-flop is ready to switch as soon as pin 4 goes high and releases the clear on the flip-flop. When the switch is closed, current will flow through R_3, causing pin 4 to go high and charging capacitor C_3.

Now that we have released the flip-flop, it can switch from the high on set input. This switch will result in the output going low and the Q output going high. The Q output will turn on the transistor and provide a discharge path for capacitor C_1, causing the voltage to drop on pin 2. When the voltage drops to 4 V, comparator #1 will switch and put a high on the reset input to the flip-flop, which will switch the flip-flop, putting a high on the output and a low on the Q out.

The output has now gone from the high it started with, to a low, and now back to a high. The low on the Q output will turn off the transistor, and capacitor C_1 will start to charge again. When the voltage at the top of the capacitor reaches 8 V, the flip-flop will switch again, and the cycle will continue as long as pin 4 stays high. When the switch is allowed to open again, capacitor C_3 will provide the high for pin 4 for a period of time as it discharges through resistor R_4.

If we were to disconnect capacitor C_3, we would only have a series of pulses from this circuit during the time that the switch was closed. We could also use another 555 timer chip to feed a pulse into pin 4 to hold it high for a specific period of time for a controlled number of pulses. As you can see, the number of possible circuits that can be obtained from 555 chips are endless.

SUMMARY

The 555 timer chip is an excellent example of the idea that complex circuits are really only a combination of simple circuits. If we had drawn the 555 timer chip showing all of the individual transistors, instead of showing the comparators as triangles and the flip-flop as a square, it would have looked too complex, and you would have had trouble understanding it. When you are faced with a large circuit composed of many transistors, remember that you can put groups of these transistors into compartments that will have certain characteristics. When we look at a complex circuit as a small group of individual circuits or compartments, instead of a large collection of transistors, it becomes easier to understand and work with. Remember that a large complex circuit is made from a collection of simple circuits.

EXERCISE: Read each question carefully, and take your time. Use your notebook paper or scrap paper to solve the problems. Round off your answer to the three most significant digits.

1. The flip-flop inside a 555 timer chip has three inputs. What should be on these inputs for the output to go high?
   A. Set high, reset low, and clear high
   B. Set low, clear low, and clear high
   C. Set low, reset low, and clear low
   D. Set low, reset high, and clear high
   E. None of the above

2. What are the 556 and 558 chips?
   A. The 556 and 558 are more complex timer circuits.
   B. The 556 is two 555s, and the 558 is four 555s.
   C. The 556 and 558 are modified op-amps.

D. The 556 and 558 are single timer chips made by other companies.
E. None of the above

3. What will the output be on the flip-flop inside a 555 timer chip if there is a low on the clear input and a high on the set input?
   A. Approximately 12 V
   B. Approximately 6 V
   C. Approximately 0 V
   D. Approximately 2 V
   E. None of the above

4. If the switch were shorted on the one shot pulse generator that you studied, what circuit would it resemble?
   A. Integrator
   B. Schmitt trigger
   C. Inverter
   D. Pulse generator
   E. None of the above

5. How long will the pulse length be with a 1 MΩ resistor and a 4 μF capacitor in the 555 timing circuit?
   A. 8.3 s
   B. 4.4 s
   C. 32.7 ms
   D. 14.7 ms
   E. None of the above

6. What are the two trigger voltages inside a 555 timer chip if V_{CC} is 12 V?
   A. 4 and 8 V
   B. 3 and 7 V
   C. 4 and 9 V
   D. 3 and 8 V
   E. None of the above

7. What is the reason for a capacitor between pin 5 and ground on the 555 chip?
   A. Improves the appearance of the circuit
   B. Reduces the possibility of oscillation
   C. Adds timing function to the control input
   D. Filters out noise and ripple
   E. None of the above

C-7

AM and FM Modulation

UNIT OBJECTIVE: Upon completion of this instructional unit, the student will be able to demonstrate a knowledge of integrated circuits and the op-amp circuit.

SPECIFIC OBJECTIVES: Upon completion of this assignment, the student(s) will be able to demonstrate a knowledge of:

- the effect of mixing frequencies
- AM and FM modulation

TERMS

Superheterodyne: A method of mixing frequencies to improve the selectivity and gain in receivers.
Period: The time it takes for a wave to complete one cycle.
Harmonic: A multiple of the primary or fundamental frequency.

HARMONICS

When we add sine waves of the correct amplitude and frequency, we can obtain square waves, sawtooth waves, or any other periodic wave. ***You have studied the basic sine wave in your trigonometry class. The sine wave is a fundamental wave in nature.*** A periodic wave is any wave that repeats itself in cycles. The *period* of a wave is the time it takes the wave to complete one cycle.

When sine waves are added to make a periodic wave, we cannot just add any frequency of sine waves. The frequency of the sine waves must all be a multiple of the frequency of the wave we are making. The multiple of a fundamental frequency is called a *harmonic*. A fundamental frequency is the frequency of the wave whether it is a square wave, sine wave, or any other periodic wave. The fundamental frequency is the frequency of the complex wave and not the frequencies of the waves that make it up. The harmonics of a fundamental wave are the multiples of the fundamental frequency increasing in frequency. For example, the harmonics of 10 kHz would be 20 kHz, 30 kHz, and 40 kHz.

A complex periodic wave, such as a square wave, will be made up of the harmonics of the fundamental frequency. We can find the specific amplitude and frequency of the harmonic sine waves needed to make up a square wave or any other periodic wave from mathematical formulas. For a square wave, the formula for finding the amplitude of the harmonics is formula 1.

$V_H = \frac{2A}{n\pi}$ *formula 1*

The square wave is made up of only odd harmonics, which means that a 10 kHz square wave would have a 10 kHz sine wave plus a 30 kHz sine wave and a 50 kHz sine wave plus an infinite number of additional odd harmonic sine waves to make up the square wave. If our 10 kHz square wave is 10 V in amplitude, then the 10 kHz sine wave harmonic would be 6.3 V, the 30 kHz harmonic would be 2.1 V, and the 50 kHz harmonic would be 1.3 V. This formula will continue to give you the amplitude of the additional harmonics. Notice that the amplitude of the harmonics drops rapidly as the frequency increases. The amplitude of the 30th harmonic or 300 kHz would be 0.2 V. Harmonics that are this far from the fundamental frequency are too small to have a significant effect on the shape of the square wave.

A spectrum analyzer is an electronic instrument that will show the different frequencies within a particular frequency range. If you fed the square wave into a spectrum analyzer, you would see the signal broken down as shown in figure 1. Notice that only the first three harmonics have a substantial output.

The periodic waves that are made up of only odd harmonics are the waves with half-wave symmetry. You can determine if a signal has half-wave symmetry by taking the negative or bottom half of the signal and mentally flipping it over to the top and then moving it back one half cycle. If the wave has half-wave symmetry, there will be a perfect match between the bottom and top halves. Periodic waves with half-wave symmetry will be made from only odd harmonics.

FREQUENCY MIXING

If you use an op-amp circuit to amplify two different frequencies, the output will simply be a mixture of the two frequencies. The op-amp amplifier is a linear amplifier, which means it will not change the shape of the input signal. Mixing two frequencies in a nonlinear amplifier will result in more than just the two frequencies. A bipolar transistor amplifier, when driven hard so the signal goes from saturation to cutoff, will have distortion. Distortion in an amplifier means the shape of the signal is changed from the input signal by the amplifier. This change in the signal results from a nonlinear amplifier. If two frequencies are mixed in this nonlinear amplifier, the output will be the two original frequencies, their harmonics, and the sum and difference of the two original frequencies, plus the harmonics and sum and differences of the harmonics and all other frequencies present.

The frequencies with significant amplitude will be the two original frequencies, their harmonics, the sum of the two original frequencies, and the difference between the two original frequencies. This is six different frequencies. The bipolar transistor when operated at the medium, signal level will primarily have just these six frequencies. A bipolar transistor amplifier that is operated at the small signal level will have very little distortion and is therefore mostly linear. The small signal bipolar transistor amplifier will not have the harmonics and difference frequencies.

The JFET, which you studied earlier, has what is called *square law distortion* resulting from the parabolic shape of the transconductance curve. When two frequencies are mixed in the JFET, this square law distortion will cause the JFET to produce the six frequencies with either small, medium, or large signal operation. The square law distortion causes it to fail to produce all the other frequencies, like the bipolar transistor amplifier with large signal operation. This gives the JFET a definite advantage over the bipolar transistor, since the other frequencies, even when they are low in amplitude, will often cause interference problems. The JFET is often used in the better radio receivers for mixing signals.

SUPERHETERODYNE

By mixing the signal from the antenna with a signal from an oscillator, in a nonlinear amplifier, we can build a better radio receiver. The difference frequency, from this nonlinear amplifier, results in a more selective radio receiver with more gain. The superheterodyne radio receiver uses the concept of mixing frequencies in a nonlinear amplifier to obtain this improved performance.

The block diagram in figure 2 shows how the circuitry in an FM radio is organized. The radio is tuned to an FM station at 100 MHz. The 100 MHz signal coming in from the antenna goes to the R.F. amplifier and tuner. Tuned circuits in the R.F. amplifier will pass the 100 MHz signal and reject all other frequencies. When the radio is tuned to other stations, the tuned circuits in the R.F. section will change their resonant frequency to the new frequency.

Notice in figure 2 that the signal is mixed in the mixer section after the R.F. section. The example shows the oscillator feeding 89.3 MHz to the mixer. This first oscillator will change its frequency when the radio is tuned to a new station.

The circuits are designed to keep the oscillator at 10.7 MHz below the desired signal coming in from the antenna. The six frequencies that come out of the mixer are listed above the filter. The filter shown after the mixer is a band-pass filter. It has a center frequency of 10.7 MHz. Only the 10.7 MHz will pass through the filter section. Most FM radios use ceramic filters in this section. The selectivity of the ceramic filters determines the selectivity of the receiver. The ceramic filters which are not tunable have a very sharp cutoff compared to the tunable tuned circuits in the front end or R.F. section.

Good-quality FM receivers will have two ceramic filters in this section. The filters will be color-coded so the manufacturer can match them in each radio. The bandwidth of an FM radio designed for the consumer market must be able to handle the 75 kHz deviation of the FM signal transmitted from the local FM broadcast station. The ceramic filters will have a bandwidth of approximately 100 kHz. They will strongly reject the signals outside their bandwidth.

The I.F. amplifier follows the mixer. I.F. stands for intermediate frequency. After the 10.7 MHz has passed the filter section, it will be amplified by the first intermediate frequency amplifier, or I.F. amplifier. This amplified 10.7 MHz signal will then go to the second mixer. It will be mixed with 10.245 MHz from the second oscillator. This oscillator is fixed and not tunable. The 10.7 MHz does not change in frequency, so there is no need to have a tunable second oscillator. There are the usual six frequencies with the difference frequency being 455 kHz.

This 455 kHz is sent through another ceramic filter. This second ceramic filter will reject all of the other frequencies generated in the mixer and pass only the 455 kHz. The signal then goes on to an integrated circuit, which will have both the second I.F. and the FM detector.

The detector is a circuit that converts the frequency-modulated signal to the original audio signal that was used to modulate the R.F. The detected signal will then be sent on to the audio amplifier and the speaker.

A receiver with two mixers is called double conversion. It converts the frequency of the signal twice. Most personal AM radios use single conversion since the AM frequency band is already low and the selectivity with a low frequency is adequate for the system. An AM radio designed for communications will often have double conversion because of the higher demands on the system.

The standard I.F. for AM is 455 kHz. The standard I.F. for FM is 10.7 MHz and then 455 kHz.

A problem that radio designers have to be avoid, when they design a new FM receiver, is the image frequency. In our example radio, if the frequency that the radio is tuned to is a weak signal and there is a strong signal at 78.6 MHz, the strong signal will get through the tuned circuits in the R.F. section with enough signal to enter into the mixer. Now the difference between 78.6 MHz and the oscillator frequency of 89.3 MHz is 10.7 MHz. This means that the unwanted signal will not be stopped by the ceramic filters.

In an FM receiver, a stronger signal will overcome a weaker signal and only the stronger signal will be heard in the speaker output. If the signal at 78.6 MHz is strong enough to overcome the rejection of the front end with enough signal to be the strongest signal in the detector, it will be the only one heard in the speakers.

AMPLITUDE MODULATION

The regular AM broadcast band frequency range is from 540 kHz to 1,600 kHz. We can use, for our example, a radio signal in the middle of the AM band, at 1,000 kHz. If we change the amplitude or the voltage of this radio signal by using 1,000 Hz tone so that the radio signal varies in amplitude at a 1,000 times a second, then we have an amplitude-modulated signal. The radio signal will change its amplitude by an amount that is proportional to the amplitude of the tone that is modulating it.

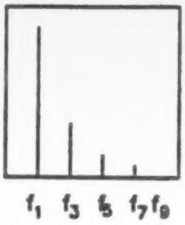
When you look at an amplitude-modulated signal on an oscilloscope, you will see what appears to be a band of light across the face of the screen. The band will have ripples on both the top and bottom, which is the modulation. This is called the *envelope* of the radio signal.

The ideal is modulate the radio signal at close to 100 percent. If we exceed 100 percent, some of the signal will be lost. To find the percentage of modulation, we can use the maximum peak-to-peak voltage and minimum peak-to-peak voltage. You can use formula 2 to find the percentage of modulation (M).

$$M = \frac{(V_{max} - V_{min})}{(V_{max} + V_{min})} \times 100 \qquad \textit{formula 2}$$

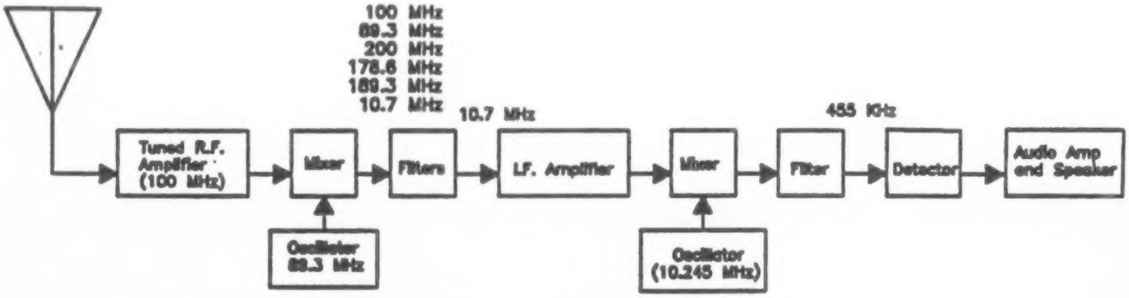
Notice that we take the difference between the maximum and minimum voltages and divide that by the sum of the maximum and minimum voltages and then multiply that by 100 to turn it into a percentage.

When we modulate an AM signal, we are mixing the two signals. This results in the total power output being equal to the sum of the radio signal and the modulating audio signal. A radio



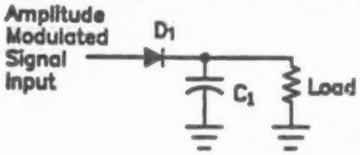
Spectrum for a Square Wave

Figure 1


100 MHz
89.3 MHz
200 MHz
178.6 MHz
189.3 MHz
10.7 MHz
10.7 MHz
455 KHz
Tuned R.F. Amplifier (100 MHz)
Mixer
Oscillator 89.3 MHz
Filters
I.F. Amplifier
Mixer
Oscillator (10.245 MHz)
Filter
Detector
Audio Amp and Speaker

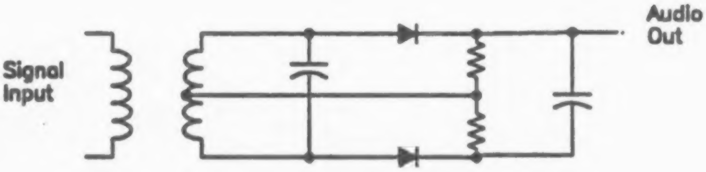
Block Diagram of an FM receiver

Figure 2


Amplitude Modulated Signal Input
D_1
C_1
Load

Amplitude Modulated Detector

Figure 3


Signal Input
Audio Out

Foster-Seeley FM Discriminator

Figure 4

signal that is 100 percent modulated will have an equal amount of radio signal and modulating signal.

The popular CB radios are amplitude-modulated. If you have the opportunity to test the power output from a CB radio, you will find that the power will increase when you speak into the microphone.

The circuitry that separates the audio modulating signal from the amplitude-modulated signal is relatively simple. The circuit in figure 3 is all that is necessary. Notice that this is the same circuit as a half-wave rectifier. Diode D_1 will clip off the bottom half of the envelope. This will leave the top half or positive part of the signal for the capacitor.

If this were a half-wave rectifier, we would use a capacitor that would filter the total signal to dc. For an amplitude-modulated detector, the capacitor must have sufficient reactance to not affect the audio and a low enough reactance to short the high frequency radio signal to ground.

The final signal will be a varying dc signal that is varying at the audio rate or is following the envelope of the radio signal. The value of the capacitor is important. It has to be small enough to have a high reactance to the audio signal and large enough to have a low reactance to the radio signal.

Mixing the audio and radio signal results in many different frequencies, as you would expect. If we feed an AM signal into a spectrum analyzer, we would see the primary signal at the frequency of the radio signal or carrier and a smaller signal on each side of this primary signal. These smaller signals on each side are called the *sidebands*. The upper sideband is for the one that is higher in frequency, and the lower sideband is for the low side. The spectrum analyzer will show these sideband frequencies wiggling back and forth in time with the modulating signal. They will be changing frequency with the frequency of the modulating signal.

The frequency of the lower sideband is equal to the center or carrier frequency minus the audio or modulating frequency. The frequency of the upper sideband is equal to the carrier plus the modulating signal. All of the information being transmitted is carried in the sidebands. The carrier or primary frequency is only necessary as a reference for the sidebands.

The single sideband radio removes the carrier and only transmits the sidebands. This radio has filters to remove the carrier and one sideband. Only one sideband is transmitted. Since all of the information is contained in each of the sidebands, it is not necessary to transmit the complete signal. The problem with the single sideband radio is filtering out the extra sideband and the carrier in the transmitter and detecting the single sideband signal in the receiver. The filters have to be very good at the transmitter end. At the receiver end, the circuitry has to add the carrier back to the sideband to detect it.

The older single sideband radios have a knob on the face of the radio which is used to adjust the frequency of the inserted carrier that is added to the sideband. The inserted carrier came from a beat frequency oscillator, and the knob was often labeled "beat frequency oscillator." When the inserted carrier is off frequency, the resulting audio will be either high or low in frequency depending on the frequency of the inserted carrier. This is where the squeals and howling come from on single sideband radios.

Some of the new developments in single sideband technology have resulted in the transmitter sending an audio tone that is used as a reference by the receiver for fixing the frequency of the inserted carrier. This complex technology appears to work very well.

FREQUENCY MODULATION

A high-frequency oscillator that is used to generate a radio signal can be modulated by changing its frequency. If a parallel resonant circuit, or tank circuit, is used to determine the frequency of the oscillator, then the resonant frequency of the tank circuit can be changed. A varicap diode, which is a diode that will change its capacitance with changes in voltage, can be put in parallel with the tank circuit.

The varicap diode can then be used to modulate the frequency of the oscillator. By feeding the audio signal to the varicap, the changing voltage across the varicap diode will change its capacitance, which will change the frequency of the oscillator. The stronger the amplitude of the audio signal, the greater the shift in frequency.

An FM radio transmitter will start by modulating the oscillator, which is the first stage of a radio transmitter. The oscillator can be from three to twelve or more times lower in frequency than the final output frequency. The frequency of the signal is increased from the oscillator by using class C doublers and triplers. Remember that class C circuits will remove any amplitude variations from the signal. The class C circuit cannot be used to amplify an AM signal.

The Federal Communications Commission (FCC) was established by the government to set standards for radio services. The FCC has set limits for the maximum deviation allowed for FM transmitters. The commercial broadcast FM transmitter must not deviate more than 75 kHz, and the ordinary two-way radio used by police and fire departments must not deviate more than 5 kHz.

The circuit in figure 4 is used to detect an FM signal. This circuit is called the Foster-Seeley FM discriminator. The coil would be tuned to the center frequency, and the signal's phase differences from the center frequency would result in a voltage on the output. Although the Foster-Seeley discriminator circuit was once popular, designers today prefer not to use coils in their circuits. Coils cannot be added to integrated circuits, and they are too bulking and expensive to be used in a circuit.

The system that is preferred today is the *phase-lock loop*. The phase-lock loop uses feedback to set a voltage-controlled oscillator to the center frequency. The phase difference between the signal and the center frequency results in the audio out. The complete discriminator circuit can be put in an integrated circuit. No tuning of bulking coils is necessary with the phase-lock loop circuit. The center frequency of the phase-lock loop is set by a fixed resistor.

EXERCISE: Read each question carefully, and take your time. Use your notebook paper or scrap paper to solve the problems. Round off your answer to the three most significant digits.

1. The FCC has set a maximum deviation for commercial broadcast stations. What is this maximum deviation?
   A. 5 kHz
   B. 75 kHz
   C. 45 kHz
   D. 1,600 kHz

E. None of the above

2. Which section of a radio receiver will provide most of the selectivity?
   A. Filter section
   B. I.F. section
   C. Mixer section
   D. Tuned circuits in the R.F. amplifier
   E. None of the above

3. What is a *beat frequency oscillator*?
   A. An oscillator that develops a musical beat
   B. An oscillator used in an AM transmitter
   C. A type of mixer oscillator
   D. A signal used to complete a single sideband signal
   E. None of the above

4. What is the basic wave that is found in nature?
   A. Square wave
   B. Flat wave
   C. Sawtooth wave
   D. Sine wave
   E. None of the above

5. What is the frequency of the first I.F. in an FM receiver?
   A. 455 kHz
   B. 100 MHz
   C. 10.7 MHz
   D. 89.3 MHz
   E. None of the above

6. Which of the following signals will have both odd and even harmonics?
   A. Square wave
   B. Sine wave
   C. Signal output from a bridge rectifier
   D. Triangle wave
   E. None of the above

7. What is the I.F. in a single conversion AM receiver?
   A. 10.7 MHz
   B. 455 kHz
   C. 100 MHz
   D. 89.3 MHz
   E. None of the above

8. What is the Foster-Seeley circuit?
   - A. FM detector circuit
   - B. AM modulation circuit
   - C. FM modulation circuit
   - D. AM detector circuit
   - E. None of the above

9. What is it called when the audio signal changes the carrier frequency?
   - A. Audio detection
   - B. Amplitude modulation
   - C. Frequency modulation
   - D. Error detection
   - E. None of the above

C-8

Video Monitoring Systems

UNIT OBJECTIVE: Upon completion of this instructional unit, the student will be able to demonstrate a knowledge of integrated circuits and the op-amp circuit.

SPECIFIC OBJECTIVES: Upon completion of this assignment, the student(s) will be able to demonstrate a knowledge of:

- video transmitting systems
- video receiving systems

TERMS

Primary colors: The primary colors used to produce color pictures on a video monitor are red, blue and green.

VIDEO SYSTEMS

Your study of small particle behavior, light energy, and Boyle's gas laws in your physics courses will help you understand the following concepts. To comprehend video monitoring systems, you need to understand how the eye can see an image when only a pattern of dots is presented. When very little light is available, the pupil of the eye is wide open, and the light available is focused over the total back part of the eye, or the retina.

The eye can only see color through the color cones in the center of the retina. To see color, there must be enough light to cause the eye to focus the image only on the small area that has the color cones. A video screen, with a low light level, will not show color if the eye cannot focus the image down to the color cones. When the image is spread out over the whole retina, there will not be enough of the image on the color cones to see color.

The eye also has the ability to see the total image when the picture is composed of many small dots. Pictures in newspapers and magazines are made up of many small dots. If you magnify the picture in a magazine or newspaper, you will be able to see the individual dots. When you are looking at a picture at the proper distance and the dots are of the proper size and spacing, the eye does not see the dots, only the image. Guidelines have been established for engineers to help them design video systems that are compatible with the human eye.

The human eye will also see new colors when colored dots are used in pictures. When you mix some colored paints, the result is a totally different color. When red and blue dots are mixed in a picture and viewed from a distance, the observer will see purple.

Only the three primary colors—red, green, and blue—are necessary to produce the full range of colors on a color monitor. These three colors—red, green, and blue—are the primary colors on a video monitor and not the artist's or printer's primary colors.

The ability of the eye to take individual pictures that are presented to the eye in series and to see a smooth transition is important to the design of equipment. The numbers of pictures per second, or the rate at which the pictures have to be presented, depends somewhat on the level of light presented. The more light there is, the faster the pictures can be presented. Ordinary motion pictures are not as bright as color video monitors. The motion picture display will present a smooth transition with 48 pictures per second. Color video must present 60 pictures per second to avoid any flicker.

The image is generated on a video screen by scanning an electron beam across the face of the tube from left to right starting at the top. The U.S. standard calls for 525 lines across the face of the screen. Other countries have slightly different standards.

The block diagram in figure 1 shows all the information coming from the receiver section. The receiver section is a radio receiver. The picture is transmitted using amplitude modulation, and the sound using frequency modulation.

If the monitor were receiving the picture over a cable system, then the receiver section would not be necessary. This same organization is used for video monitors on computer systems. The difference between a monitor used for displaying pictures, such as a surveillance monitor, and a computer monitor is that the computer monitor uses electrostatic deflection to move the electron beam in the picture tube, and a surveillance monitor uses magnetic deflection.

Figure 1 also shows the decoder and the three color amplifiers. The decoder decodes the signal, providing the information for the three colors, and then amplifies the information. This information is then sent to the color gun on the picture tube.

The color synchronizing section contains a 3.579 MHz oscillator that is synchronized with the color reference burst. The color reference burst comes from the horizontal synchronization and blanking pulse which is part of the signal.

Getting the picture on the face of the tube requires the different sections to be synchronized. The horizontal and vertical sweep sections provide the focus and blanking signals to the picture tube. The high-voltage section provides the high voltage for the anode of the picture tube. Both the vertical and horizontal sweep sections have oscillators that are synchronized with the appropriate pulses in the incoming signal.

One section that is not shown in figure 1 is the Y amplifier. This section provides a slight time delay to the brightness so it arrives at the picture tube at the same time as the color information. The color information has to go through many more circuits than the brightness.

The high-voltage section uses a flyback transformer and possibly a voltage tripler to develop up to 30,000 V for the anode of the picture tube. The high-voltage tripler in some of the earlier monitors was a source of many failures.

PICTURE TUBE

Many companies are investing research time and money to replace the picture tube. The picture tube is the last vacuum tube component that has not been replaced by semiconductors. Liquid

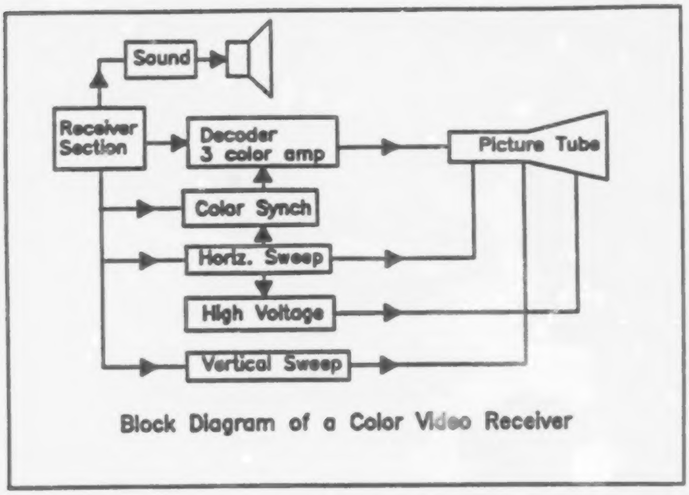

Sound
Receiver Section
Decoder 3 color amp
Picture Tube
Color Synch
Horiz. Sweep
High Voltage
Vertical Sweep
Block Diagram of a Color Video Receiver

Figure 1

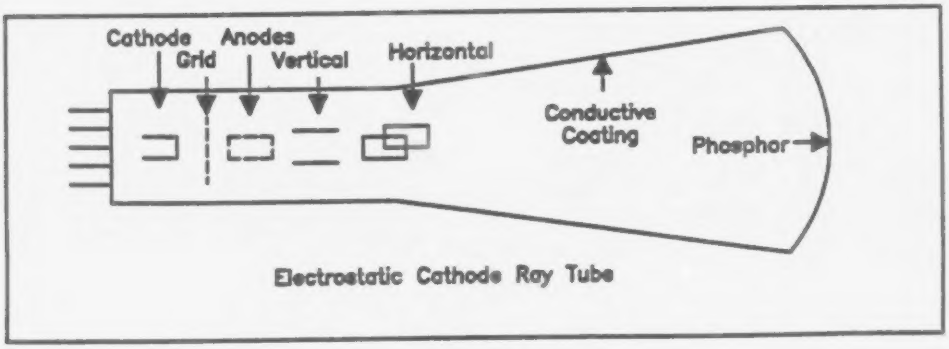

Cathode
Grid
Anodes
Vertical
Horizontal
Conductive Coating
Phosphor
Electrostatic Cathode Ray Tube

Figure 2

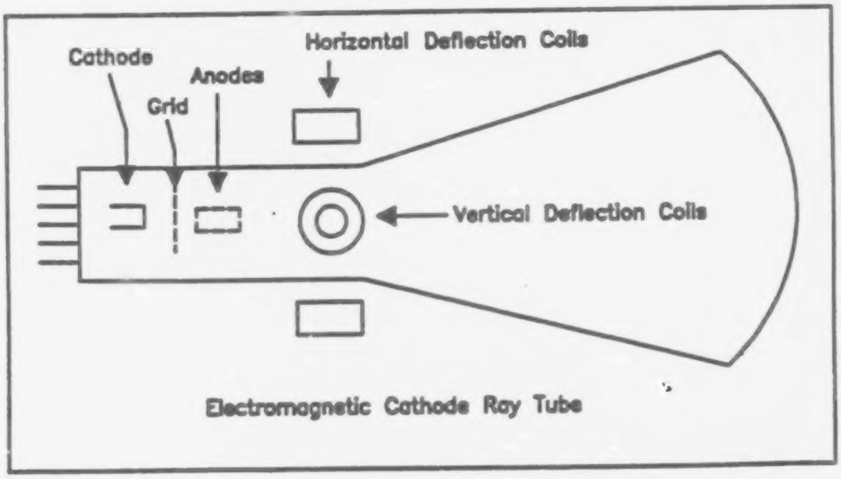

Cathode
Grid
Anodes
Horizontal Deflection Coils
Vertical Deflection Coils
Electromagnetic Cathode Ray Tube

Figure 3

crystal display systems have some promise of replacing it in the future. The new laptop portable computers use the LCD instead of the vacuum tube.

The picture tube, which is a vacuum tube, has a heated filament that boils off the electrons. There is a vacuum inside the glass envelope, so the electrons are free to move around without bumping into other air molecules.

Once they are free of the filament, the electrons are attracted to the positively charged plate or anode. A grid is placed between the anode and the filament to control the flow of electrons. The grid is a fine mesh wire. When the grid is biased negative, the electrons will be repelled from the grid and blocked in their path to the plate.

Figure 2 shows one type of picture tube, a cathode-ray tube. The cathode, grid, and anodes can be considered the gun portion of the tube, firing electrons toward the phosphor-coated face of the tube. A very good vacuum exists inside the tube so there will be nothing to interfere with the movement of the electrons. The anodes shown are used to speed up the electrons.

The gun forms the electrons into a narrow beam, which is controlled by the vertical and horizontal deflection plates. These plates will attract or repel the electrons by electrostatic force.

Inside the glass tube and around the front of the tube is a conductive coating. The conductive coating is not across the face of the tube. A very high positive voltage is placed on this conductive coating to attract the electrons.

To summarize, the electrons are emitted by the cathode, speeded up and formed into a narrow beam, and then controlled by the vertical and horizontal deflection plates. The electrons are attracted towards the high positive potential of the second anode or coating inside the tube. The vertical deflection plates control the vertical position of the beam, and the horizontal deflection plates control the horizontal movement of the beam.

The electrons, which strike the phosphor coating on the face of the tube, exchange their energy for light. The spent electrons then drift to the conductive coating or anode located around the inside of the tube. The electrostatic deflection method requires very high voltages to deflect the electron beam. Very little current is required in the process of deflecting the electrons. Oscilloscopes and computer monitors will usually have this type of picture tube.

Figure 3 shows the electromagnetic system in a cathode-ray tube. The electromagnetic deflection cathode-ray tube has basically the same gun arrangement as the electrostatic tube. The difference between the two systems is that the electromagnetic tube uses magnetism and the electrostatic tube uses an electrostatic charge to control the electron beam.

Notice, in figure 3, the horizontal deflection coils on the top and bottom of the tube. Remember from your study of magnetism that an electron beam will be deflected at right angles to the magnetic lines of force. The magnetic fields that are necessary to deflect the electron beam require large amounts of current. The electrostatic system requires large voltages.

A major advantage of the magnetic deflection system is that a much greater deflection can be achieved. As a result, a shorter tube can be used with a large face. Video monitoring systems and television systems use picture tubes that have the magnetic deflection method. This results in smaller cabinets for the picture monitors.

VIDEO CAMERAS

The camera used to create the picture shown on a video monitor is made using a video camera tube and the supporting electronics. The video camera tube can be made using the principles of either the image orthicon or the vidicon.

The *image orthicon* camera tube has a photoemissive cathode which the light is focused on. A photoemissive surface will give off electrons when light strikes it. Remember that a cathode is the source of electrons in a regular video picture tube. The photoemissive surface is the source of electrons when light strikes it. This part of the tube will have a -500 V potential on it. There is an inner conductive coating with a +150 V on it to attract the electrons from the photoemissive surface.

The electrons strike a target which is an array of small insulated cells. There is insulating material on the back side of this array and then more insulated cells directly across from the cells that have been struck by the electrons. The cells struck by electrons build up a negative charge which by capacitive action results in a positive charge on the cells across from them. An electron beam coming from a gun similar to the type of gun in a cathode-ray tube scans the cells that have the positive charges. As the electrons from the gun strike the positive-charged cells, some electrons are given up. The amount of electrons the beam loses depends on the charge of the cell, which depends on the amount of light received by the photoemissive surface.

The electrons that are left in the beam return toward the gun. The return beam is very weak and is collected by an electron multiplier arranged around the gun output. This electron multiplier amplifies the weak return beam. The result is an amplitude-modulated electron beam which is amplified by the electron multiplier. The output from the electron multiplier is the signal from the tube. This type of camera is not as common as the vidicon camera.

The image orthicon camera is very sensitive, but difficult to set up and use. The vidicon camera tube is not as sensitive, but it is more stable and easier to use. The vidicon is the most popular tube used today.

The light coming into a *vidicon* tube will pass through a transparent conductive layer and strike the insulated cells of the photosensitive material. Each of these cells will change its resistance according to the amount of light it receives. No light will result in maximum resistance. A beam of electrons is used to scan the cells, just as in the image orthicon tube. The electron beam will pass through the photosensitive material and strike the conductive material. The current flow in the conductive material will depend on the resistance of the photosensitive material. The amount of current coming from the tube depends on the amount of current coming from the electron beam and the modulating resistance in the photosensitive material. There are many varieties of vidicon tubes.

EXERCISE: Read each question carefully, and take your time.

1. What three colors are used for the three color guns in a picture tube?
   - A. Blue, yellow, and red
   - B. Green, yellow, and red
   - C. Red, blue, and green

D. Orange, yellow, and violet
E. None of the above

2. How many scanning lines are there across the face of the picture tube?
A. 750
B. 525
C. 425
D. 375
E. None of the above

3. How many video pictures have to be presented per second to avoid flicker on a video monitor?
A. 250
B. 45
C. 120
D. 60
E. None of the above

4. What does the grid do in a picture tube?
A. Screens out the electrons
B. Controls the amplitude of the electron beam
C. Changes the direction of the electron beam
D. Attracts the electrons
E. None of the above

5. How high are the voltages on a picture tube?
A. From 10,000 to 30,000 V
B. From 60,000 to 120,000 V
C. From 5,000 to 15,000 V
D. Over 130,000 V
E. None of the above

6. What happens to the electrons after they strike the phosphor coating on the face of the tube?
A. They drift to the anode or conductive coating inside the tube.
B. They are absorbed by the positive ions in the tube.
C. They remain imbedded in the phosphor coating.
D. They bounce back toward the gun.
E. None of the above

7. What is the primary advantage of the electromagnetic deflection system over the electrostatic deflection system?
A. The electromagnetic system requires less current.
B. The electrostatic deflection is more expensive.
C. The electromagnetic system can achieve greater deflection.
D. The electromagnetic system is not affected by voltage surges.
E. None of the above

Unit

D

Digital Basics

D-1: Introduction to Digital
D-2: Binary, Hex, and Decimal Systems
D-3: Logic Gates and Diagrams
D-4: Boolean Algebra
D-5: XOR and XNOR

D-1

Introduction to Digital

UNIT OBJECTIVE: Upon completion of this instructional unit, the student will be able to demonstrate a knowledge of numbering systems with different bases, work with logic gates, understand logic diagrams, and be familiar with Boolean algebra.

SPECIFIC OBJECTIVES: Upon completion of this assignment, the student(s) will be able to demonstrate a knowledge of:

- the relationship between processing and memory circuits
- the different troubleshooting methods used in digital circuits

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TERMS

Memory: A memory circuit will retain its output when the input is removed.
Microprocessor: This integrated circuit includes most of the necessary parts of the computer.

DIGITAL VERSUS ANALOG

Your studies in algebra and trigonometry will help you understand the difference between analog and digital. When we present a number using an analog representation, we will present a quantity that is proportional to another quantity. *In an analog system, change is proportional.* The sound pressure on a microphone is proportional to the voltage output from the microphone. This would be an analog function. When we count something like the gallons of gasoline in the fuel tank of a car, an analog system will have a meter with a pointer that moves to a position to indicate how full the tank is. The pointer will move slowly down towards empty as the gasoline is used.

If you replaced the meter with a digital meter to provide a digital system for counting or measuring the amount of gasoline, then the readout does not change proportionally with the quantity of gasoline. If the digital meter reads to the nearest tenth of a gallon, then as the gasoline is used between tenths, there is no change on the readout. *The digital system changes abruptly in increments,* according to its design. Digital systems will generally be more accurate, although the total accuracy usually depends on the increments in the digital readings. If the digital meter reads to a tenth, then you cannot get a reading any closer than a tenth. An analog system will allow you to examine the pointer and estimate the reading to higher levels.

Engineers will often design an analog system to be accurate within some percentage of full-scale reading. Any attempt to read the pointer of an analog system any closer than the design tolerance will be subject to error. A digital system is usually as accurate as the readout. If the system says there are 3.5 gallons of gasoline still in the tank, then there will be from 3.45 to 3.55 gallons. An analog meter with 10 percent full-scale accuracy, which is common, can be as much as a gallon off, if the maximum or full position reads 10 gallons. This means the position of the pointer can be as much as one gallon off from the actual amount of gasoline left in the tank.

Digital systems also allow the data to be stored in memory systems. Often an analog system will be converted to digital using an A/D converter. This will take the analog voltage and convert it to a group of outputs with highs and lows that indicate the numerical value of the quantity.

Many circuits and electronic devices that were once analog in nature have been converted to digital. The telephone company converts your voice, which is analog in nature, to digital signals before sending it down the line. Most industrial process controls are digital and are often microprocessor-controlled.

MICROPROCESSOR-CONTROLLED CIRCUITS

It is not uncommon for designers to develop a piece of digitally controlled equipment to perform a certain job. Then, in order to sell more of this equipment, the designers add extras to it. Finally, the extra control functions justify a microprocessor for control.

A microprocessor is the brains of the computer, all in one integrated circuit. Memory and interface chips can then be added, if necessary, to supplement the circuitry. Adding a microprocessor often changes the structure of the control, and usually results in a much better control system than just ordinary digital control.

An ordinary digital circuit will have a specific output while it is receiving a particular input. Memory circuits can be added to a simple digital circuit to improve it. When a particular size is reached, the circuit becomes complex enough to justify switching to a microprocessor-based circuit. Some city governments have found that switching their digital control traffic lights to microprocessor control has saved them a lot of money. It also allowed them to include remote control features that were difficult to add with the old system.

A system that is microprocessor-based is a system operated by computer. The computer will have what is called a *clock*, which is actually an oscillator. This oscillator is used to keep the operations in sequence and for timing the operations. A digital circuit that is not microprocessor-based will not operate in sequence. The digital circuit will have a certain output based on the inputs. When the process is done in sequence, an input will start a series of outputs, and additional inputs can be added when the sequence is ready for them.

The path that the sequence of operations follows, or the set of instructions given to a microprocessor-controlled system, is called the *program*. For a simple microprocessor-based system that is used to control a microwave oven, there is an integrated circuit memory chip with the program written in its memory. The program will cause the microprocessor to take the steps that are needed in sequence.

The first step would be to check for an input from the control panel. When it receives this input, it will energize its circuits and wait for more inputs. The next inputs may give it information on heat level and time to turn on and off. If you wanted to change the way the oven handled the instructions you gave it, you would have to remove the memory chip with the programming instructions and change those instructions. Changing the instructions may involve changing the chip or just rewriting the instructions into the chip.

COMPUTER MEMORY CIRCUITS

Digital circuits that have memory circuits can hold their output when the input is removed. A digital circuit without a memory function may go high on its output when it receives a particular input. When that input is removed, the circuit goes back to its normal low state. A memory circuit can put a high on its output when it receives an input and then stay high until it receives another input which would cause the output to go low.

Digital memory circuits are able to store data by keeping a specific voltage level on their output until they receive an input that causes them to change that output. The integrated circuits that are used for storing data are called ROMs and RAMs. ROM stands for *read only memory*. A ROM is usually programed at the factory and cannot be changed in the field. RAM stands for *random access memory*. The RAM is usually thought of as the same as an RWM (*read write memory*). The RAM can be used for temporary storage and can be written into and read during the computer's operation. This means that the data generated during an operation can be stored in a RAM. A program that does not normally need to be changed that often could be stored in a ROM. A RAM will normally require a continuous source of power to maintain its memory, while a ROM will store its memory with or without power.

Another method of storing data is on floppy disks, hard disks, and various tape storage methods. These methods do not require power to maintain their memory, but are usually much slower to access than either a RAM or a ROM.

DIGITAL INTEGRATED CIRCUITS

Today most digital circuits are built using integrated circuits. The number of discrete components used in a digital circuit has become very few. There are industry standards established for the design of integrated circuits used in digital circuits.

The two drawings in figure 1 show the outline for two variations of the standard 14-pin DIP. The term *DIP (dual inline parallel)* refers to the arrangement of the pins on the chip. A small cutout at one end of the plastic that covers the chip is there to help identify where pin number 1 is. If you are looking at the chip with the cutout at the top, then pin 1 is to the top left. The pins are numbered down that side and across and up the other side.

For the style on the left, pin 14 is reserved for V_{CC} and pin 7 is used for ground. The style on the right puts both the V_{CC} and ground in the center of the chip to help in laying out the pattern on the board. For the style on the left, the 16-pin DIP will have pin 8 for ground and pin 16 for V_{CC}.

The bigger memory chips and microprocessor chips will have many more than just 16 pins. The manufacturers of these chips supply data on their products which will list the uses for each of the pins on the chip.

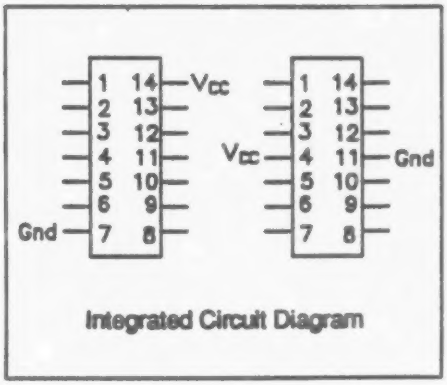
Vcc
Gnd
Vcc
Gnd
Integrated Circuit Diagram

Figure 1

TEST EQUIPMENT

The most common digital circuits use 5 V as their logic high and 0 V as their logic low. The various resistance losses in the circuitry will result in voltages that vary from the 5 V or 0 V. It is not critical for the circuitry to have voltages at exactly 5 V or 0 V. Some ICs are sensitive to voltages above 5 V and can be damaged if the power supply were to exceed that voltage.

Digital circuits are usually designed to respond to voltage pulses. A common problem called *switch bounce* can occur if an ordinary mechanical switch is used to feed pulses into a digital circuit. The switch will bounce when it is closed, causing additional pulses to be sent. This can be frustrating when you want only one pulse. By using a simple memory circuit called a debounce switch, only the desired pulses will be generated.

Since digital circuits operate using pulses, there is test equipment designed specifically for digital and computer circuits. One common piece of digital test equipment, which is valuable for testing simple digital circuits, is the *logic probe*. This instrument will light up an LED when it sees a high and another LED for a logic low. A good logic probe will tell you when the logic voltages in the circuit are out of limits. Also, the *logic analyzer*, an expensive piece of equipment, is designed to show the data that may exist at many different points at once. This can help a technician see the difference in timing between different inputs to a chip.

EXERCISE: Read each question carefully, and take your time.

1. Which of the following is a digital device?
   A. Microphone
   B. Ruler
   C. Calculator
   D. Record player
   E. None of the above

2. Where would pin 8 be on a 14-pin DIP with the notch at the top?
   A. Top left corner
   B. Top right corner
   C. Bottom left corner
   D. Bottom right corner
   E. None of the above

3. The 14-pin DIP uses which two pins for V_{CC} and ground?
   A. V_{CC} is pin 7, and ground is pin 14.
   B. V_{CC} is pin 14, and ground is pin 7.
   C. V_{CC} is pin 5, and ground is pin 10.
   D. V_{CC} is pin 1, and ground is pin 7.
   E. None of the above

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4. Which of the following is part of a microprocessor system and would not be included in a digital circuit?
   A. Memory circuits
   B. Logic voltages of 5 V and 0 V
   C. Input data in the form of pulses
   D. Program
   E. None of the above

5. What two voltages are standard for digital pulses?
   A. 0 V and 5 V
   B. 1 V and 4.5 V
   C. 0 V and 12 V
   D. 5 V and 10 V
   E. None of the above

6. What is the memory chip called that cannot be changed or programmed in the field?
   A. RWM
   B. ROM
   C. RAM
   D. PROM
   E. None of the above

7. What do you call the integrated circuit memory chip that can be changed or programmed in the circuit?
   A. RWM
   B. ROM
   C. RAM
   D. PROM
   E. None of the above

8. For what purpose is a hard disk used?
   A. To keep the program in sequence
   B. To separate out weak pulses
   C. To store data
   D. To provide a buffer between hard and soft data
   E. None of the above

9. How accurately, in gallons, will a digital display with three digits read a tank of fuel that holds 20 gallons when full?
   A. Nearest half gallon
   B. Nearest tenth of a gallon
   C. Nearest gallon
   D. 0.001 gallon
   E. None of the above

D-2

Binary, Hex, and Decimal Systems

UNIT OBJECTIVE: Upon completion of this instructional unit, the student will be able to demonstrate a knowledge of numbering systems with different bases, work with logic gates, understand logic diagrams and be familiar with Boolean algebra.

SPECIFIC OBJECTIVES: Upon completion of this assignment, the student(s) will be able to demonstrate a knowledge of—

- how to count, add, and subtract using binary numbers;
- other numbering systems; and
- how to work with other numbering systems.

TERMS

LSB: The least significant bit, or the digit on the right end of a number.

Twos complement: A method used by the computer to subtract numbers and store negative numbers.

NUMBERS

Part of what you will study in this lesson will be a review of what you studied in computer mathematics. Digital circuitry can become very complex. All digital circuits are organizations of switches. These switches have only two positions, either *open* or *closed*. As a result, all of our calculating, counting, and writing has to be done using only these two conditions, an open or a closed switch. We will often refer to these two positions of the switch as high and low. The ***high*** is typically a voltage approaching 5 V, and the *low* is close to 0 V. The voltages will vary because of the resistance within the components.

To be able to calculate and count with a machine that is limited to only two values requires a numbering system with only two values. This numbering system is called the *binary system*. The only two numbers in the binary system are 0 and 1. All mathematical functions can be done with just these two numbers.

Another numbering system, called the *hexadecimal system*, has been developed to help people deal with the computer. The hexadecimal system has 16 numbers. Since our common decimal system has only 10 numbers, the letters A through F are used for the numbers above 9. It is easy to convert from the hexadecimal system to the binary system, and it is just as easy to convert from binary to hexadecimal.

BINARY NUMBERS

Before we can understand the binary system of numbers, we need to examine the decimal system. The decimal system is the system you have been using since you started school. ***You should be familiar with the concepts of the decimal system from your study of number theory in beginning algebra.***

The decimal numbering system is a positional system. In a positional system, the position of a number will give the magnitude of the number. For example, the number seven hundred thirty-six is written in its number form as 736. The 6 is in the *units* position, which means six individual units. The 3 is in the *tens* position, which means three tens or thirty, and the 7 is in the *hundreds* position, which gives the seven hundred. If we add the 700 to the 30 and the 6, we have 736. We can write this in an algebraic form.

$$(7 \times 10^2)+(3 \times 10^1)+(6 \times 10^0) = 736_{10}$$

Notice the 6 times 10 to the 0 power. Any number which is taken to the 0 power is equal to one. The 6 times 10 to the 0 power is the same as 6 times 1. Also notice the subscript 10 at the end of the 736. This indicates the number 736 is to the base 10. Our decimal system is a *base 10* system. This is why each number is multiplied by 10 to some power. The binary system is a *base 2* system. The binary number 1101_2 can be written out in algebraic form as we did for the decimal number.

$$\begin{array}{l}(1 \times 2^3)+(1 \times 2^2)+(0 \times 2^1)+(1 \times 2^0) = 1101_2 \\ 8 \quad + \quad 4 \quad + \quad 2 \quad + \quad 1 \quad = 15_{10}\end{array}$$

We can use the decimal system as a guide to help us to learn how to count in binary. The same rules apply to the binary system as the decimal system. When we count in decimal, we count up to 9 and then add the 1 to the left and start over again. The binary system has only the two numbers, but it does the same thing.

Decimal	Binary	Decimal	Binary	Decimal	Binary
0	0	6	110	12	1100
1	1	7	111	13	1101
2	10	8	1000	14	1110
3	11	9	1001	15	1111
4	100	10	1010	16	10000
5	101	11	1011	17	10001

Two terms are used in numbering systems to identify the end of the number we are talking about. The term *LSB* or *least significant bit* indicates the digit on the right end, or the least significant of the digits. The term *MSB* or *most significant bit* indicates the digit on the left end. This is where the most significant bit or digit is. A bit is one digit and is normally used in binary.

The bit is also the smallest unit in binary math. A nibble is 4 bits, and a byte is 8 bits. Computer memory is often shown as being a certain number of bytes.

HEXADECIMAL NUMBERS

Now let's examine the hexadecimal system in detail. The hexadecimal system is a *base 16* system with 16 digits. Remember that we need to use the letters from A to F to complete the hexadecimal system.

Decimal	Hexadecimal	Decimal	Hexadecimal
0	0	11	B
1	1	12	C
2	2	13	D
3	3	14	E
4	4	15	F
5	5	16	10
6	6	19	13
7	7	24	18
8	8	25	19
9	9	26	1A
10	A	28	1C

We can write the hexadecimal number 482_{16} to show its positional nature.

$$(4\text{x}16^2)+(8\text{x}16^1)+(2\text{x}16^0) = 482_{16}$$
$$1024 \quad + 128 \quad + \quad 2 \quad = 1154_{10}$$

NUMBER CONVERSIONS

There are different methods for converting from one numbering system to another. The best method for converting from decimal to either binary or hexadecimal is to divide by the base number. Study the following example to see how the decimal number 18_{10} can be converted to a binary number.

$\frac{18}{2}$ = 9 + a remainder of 0 which becomes the LSB.

$\frac{9}{2}$ = 4 + a remainder of 1 which is next to the LSB.

$\frac{4}{2}$ = 2 + a remainder of 0 which is the next digit.

$\frac{2}{2}$ = 1 + a remainder of 0 which is the next digit.

$\frac{1}{2}$ = 0 + remainder of 1. This is the MSB of our number.

The number $18_{10} = 10010_2$.

In the example above, we took the 18 and started by dividing it by the number 2. The number 2 is the base number for the binary system. The number 18 divided by 2 leaves a remainder, which is the LSB or least significant bit of the binary number. The quotient is then divided again, and this process is continued until the quotient is 0.

We can use the same system of dividing by the base number to convert from decimal to hexadecimal. The number 933_{10} can be converted to hexadecimal, as we have shown in the following example.

$\frac{933}{16}$ = 58 + remainder of 5, which is the LSB.

$\frac{58}{16}$ = 3 + remainder of 10, or A, which is the next digit.

$\frac{3}{16}$ = 0 + remainder of 3, which becomes the MSB.

The hexadecimal number becomes $3A5_{16}$.

As we have shown, the decimal number 933_{10} is equal to $3A5_{16}$ in hexadecimal. If you want to convert from binary or hexadecimal to decimal, just multiply the digits by their base to the power for that position.

For example, 1011_2 becomes $(1 \times 2^3)+(0 \times 2^2)+(1 \times 2^1)+(1 \times 2^0)$. When you do the multiplying and addition, you have the decimal number 11_{10}.

The *octal* system, which is to the base 8, is occasionally used with computer systems. The conversion methods are the same for that system as well.

COMPUTER ADDITION AND SUBTRACTION

The binary system is difficult for people to use. The hexadecimal and octal systems are used to help people working with computers that use only the binary numbering system. When you need to add or subtract with hexadecimal or octal numbers, it is usually easier to convert them to decimal, and then convert the sum or difference back to hexadecimal or octal.

It is not important to know how to add and subtract in binary. What is important is to know how the computer does the adding and subtracting in binary. The *2s complement* system is the most common system used by computers to subtract binary numbers.

Computers operate with certain word sizes. A word is a certain number of bits which is used by the computer. A specific word size is necessary because the whole system must have the capability of handling this size word. If the word that is put in this spot is smaller than the total space available, then the bits to the left of the number will be filled with zeros.

To illustrate the 2s complement system, we will use a 5-bit word size. This means the number 3 in binary will be 00011_2. We will start our example by keying into our computer the number -8. The computer will first take the number 8 and convert it to binary.

8 = 01000

Then the minus sign will cause the computer to complement the number, which causes all the 0s to become 1s and all the 1s to become 0s. One bit is then added to the complemented number, and the result is a negative binary number in the 2s complement system.

-8 = 10111 + 1 = 11000

The computer can identify this as a negative number by the 1 in the MSB position. The process of making the 2s complement will always put a 1 in the MSB position, provided there are more spaces in the word size than the size of the number that is filling those spaces.

Next we can load a +3 into the computer and add the two numbers.

-8 = 11000
+3 = 00011
-5 11011

Adding the two binary numbers gives us the result of 11011. Notice that there is a 1 in the MSB position. This makes it a negative number. To find the value of the negative number, we go through the 2s complement process of changing 1s to 0s and 0s to 1s and adding 1.

-5 = 11011
complement 00100
add 1 +1
5 = 00101

The computer would then display the number 5 on the screen with a minus sign in front of it. If two positive numbers are added, then the process is simply addition. The computer has special circuits that are used to add binary numbers. The 2s complement system allows the same addition circuits to be used to subtract numbers and handle negative numbers. To multiply and divide, the computer just adds and subtracts a large number of times.

BCD SYSTEM

The BCD (binary coded decimal) system is a common variation to the standard binary numbering system. The BCD system uses a 4-bit binary number for each of the ten decimal numbers. Remember that the number 0 is included in the ten decimal numbers and the number 10_{10} is not.

The decimal number 63_{10} would involve 8 bits in BCD as follows.

63_{10} = 0110 0011

Notice that we separate the groups of 4 bits when writing a BCD number. Since each BCD number has four bits, the unused bits to the left are zeros. A 4-bit binary number that is larger than the binary code for 9 is an illegal number in BCD. The binary number 1100 would not be a valid BCD number since it represents the number 12. The number 12 in decimal is equal to 0001 0010 in BCD.

EXERCISE: Read each question carefully, and take your time. Use your notebook paper or scrap paper to solve the problems.

1. What is the number 37_{10} in binary coded decimal?
   A. 100101
   B. 0011 0111
   C. 0100 0101
   D. 0011 0011
   E. None of the above

2. Convert the number 14 to hexadecimal.
   A. B
   B. C
   C. D
   D. E
   E. None of the above

3. What is there about a binary number in the 2s complement system that allows the computer to recognize it as a negative number?
   A. It is an illegal binary number.
   B. It always has a 0 in the LSB position.
   C. The 1 is in the MSB position.
   D. The number becomes a true binary when inverted.
   E. None of the above

4. Change the number 111011_2 to hexadecimal.
   A. 32_{16}
   B. 3A
   C. 33B
   D. 3C
   E. None of the above

5. What would the base of a numbering system be if it only had the digits 0, 1, 2, and 3?
   A. Base 3
   B. Base 4
   C. Base 5
   D. Base 6
   E. None of the above

6. Counting up, what are the next five digits that follow the number $F9E_{16}$?
   A. F9F, F00, F01, F02, F03
   B. F9F, F10, F11, F12, F13
   C. F9F, FA1, FA2, FA3, FA4
   D. F9F, FA0, FA1, FA2, FA3
   E. None of the above

7. What is the number -5 in its 2s complement form of a binary number?
   A. 0011_2
   B. 1011_2
   C. 1110_2
   D. 1101_2
   E. None of the above.

8. The highest digit in the decimal system is 9. What is the highest digit in the octal system?
   A. 8
   B. 7
   C. 6
   D. 5
   E. None of the above

9. What two decimal numbers represent the largest 3-bit and the largest 4-bit binary numbers?
   A. 8 and 16
   B. 9 and 18
   C. 7 and 15
   D. 6 and 15
   E. None of the above

D-3

Logic Gates and Diagrams

UNIT OBJECTIVE: Upon completion of this instructional unit, the student will be able to demonstrate a knowledge of numbering systems with different bases, work with logic gates, understand logic diagrams, and be familiar with Boolean algebra.

SPECIFIC OBJECTIVES: Upon completion of this assignment, the student(s) will be able to demonstrate a knowledge of:

- logic symbols
- reading and drawing logic gates
- waveforms and logic gates

TERMS

Truth table: A list of the inputs and outputs for a logic gate or circuit.

Inverter: The logic that is the inverse of the input. If the input has a 0 on it, the output will have a 1.

LOGIC GATES

Digital electronics is made up of small circuits which perform a logic function. We call these small circuits *logic gates*. The logic gate is a basic circuit in digital electronics.

A logic gate will give a particular output with a certain combination of inputs. We usually refer to the input logic on any input as being either high or low. We can also use the terms 1 and 0. The 1 is a high, and the 0 is a low.

To avoid problems, it is important to remember that all inputs must have some input into them at all times. Should you leave an input open on a TTL digital circuit, the circuit will take that input high. An input that has been left open will tend to act like an antenna to any noise pulses. To avoid false inputs from noise, all input connections should be connected to either V_{CC} or ground if they are not needed.

The two basic gates are the *OR gate* and the *AND gate*. The NOT gate is simply an inverter of the logic. The OR gate combines the logic inputs by addition and the AND gate by multiplication. Two other gates, called the Exclusive OR gate and the Exclusive NOR gate, will be studied later.

OR GATE

Your study of basic algebra will help you understand the Boolean algebra presented in this lesson. The algebraic formula for the OR gate, using Boolean algebra, is (A + B). Although our examples use only two inputs, there may be many more inputs. The OR gate truth table (fig. 1) shows four different input combinations. To make a truth table and get all possible combinations of inputs, you should start at the top with all zeros and then count in binary as you go toward the bottom. When you have counted in binary to all 1s, then you have included all possible input combinations. Next, you can go back and examine each of the inputs and determine what the output should be for each input. It is customary to label the output as X. We will generally label the inputs with capital letters starting at the beginning of the alphabet.

The circuit in figure 1 showing the two diodes and the resistor is the equivalent circuit for the OR gate. You would not find this circuit in an integrated circuit. We have put it here to help you understand how the gate works.

Remember that a logic 0 is equal to 0 V and a logic 1 is equal to approximately 5 V. If we start by putting 0s on both inputs as shown at the top of the truth table, the result will be an output of 0 as well. Putting a 0 on the input is the same as grounding the input.

If we put 5 V on either one or both of the inputs of the equivalent circuit, there will be 5 V minus the diode drop on the output. A high or logic 1 on either or both inputs of the equivalent circuit OR gate will give a high on the output.

We can use the truth table to show this logic. The first input of the truth table shows all 0s, which results in a 0 on the output. The other inputs in the truth table all include at least one high, which will put the output at a logic 1 for each case.

Remember that, in addition, adding 1 will result in one more than what you are adding it to. If the other input to the OR gate is a zero, then adding 1 to it will result in a 1 on the output. Adding two 1s in an OR gate or binary math will not give us anything higher than 1.

Notice how the logic gate symbol for the OR gate has been drawn. Three curved lines are used to draw the symbol. This gate must have at least two inputs and can have as many more than two as necessary.

AND GATE

You learned how the OR gate appears to perform addition, although not the kind of addition you are accustomed to. The other basic gate is the AND gate, which will appear to perform multiplication. We can show this using Boolean algebra. The formula for the AND gate is AB.

Notice that we have used a two-input AND gate, which has resulted in the same inputs for the truth table as the OR gate. Like the OR gate, the AND gate can have any number of inputs from two on up. Since the AND gate is multiplication, the output from the gate will be 0 if any input is 0. Only when both inputs are 1 will the output be 1. If there were ten inputs, all inputs would have to be 1 to get a 1 on the output.

Remember, when you examine the equivalent circuit, that all inputs are either connected to a high or to a low. A high is approximately 5 V, and a low is ground. Grounding either of the two inputs of the equivalent circuit will drop the voltage across the resistor, resulting in 0 V on the output. For an AND gate in general, any low on the input will result in a low on the output. If we put 5 V on the inputs, the diodes will block the current, and the 5 V from the source will appear on the output.

Notice the shape of the AND gate in figure 2. The AND gate has a straight line across the back of it with the two sides being straight and meeting a semicircle to form the front of the symbol. You should learn to draw both the AND and OR gates freehand, so they can be clearly recognized. Although there are templates for drawing these symbols, the template is often not available when you need to quickly draw a logic circuit.

NOT GATE

The NOT gate has only one input and a very simple truth table. Only one input will resu only two lines for the truth table. The NOT gate inverts whatever is on its input. If there is a the input to the NOT gate, a 0 will show up on the output.

The equivalent circuit shown in figure 3 is a transistor circuit with the output taken off the collector. Remember that taking the output off the collector results in the output being 180° out of phase with the input. When the output is 180° out of phase, it has been inverted.

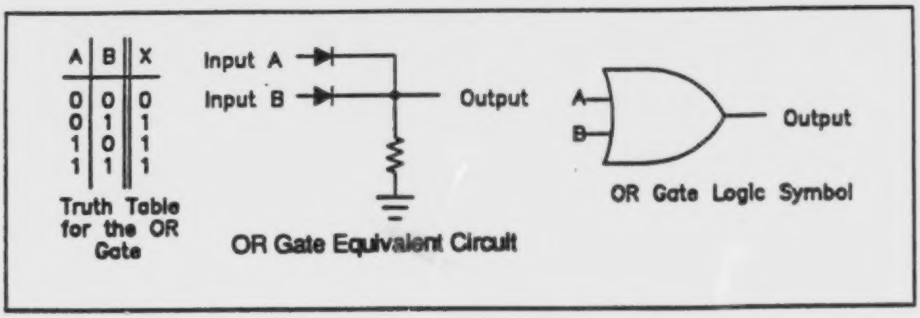
Notice that a high on the base of the transistor will turn on the transistor. This will result in current flow through the collector emitter junction, and the voltage at the collector will drop to zero. A high on the input will result in a low on the output. A low or no current into the base of the transistor will result in the transistor being turned off, and the full V_{CC} of 5 V will appear on the output.

When the NOT gate is drawn separately, we use the bubble on a triangle, as shown in figure 3. The bubble is actually the inverting part of the symbol. The triangle represents a buffer or an amplifier, which can be used to match up to other circuits. You will often see the bubble on the input and output of other gates and circuits. A bubble on the input or output indicates that the logic is inverted and also indicates that the active condition of the input or output is low. Remember that the bubble on the input to a logic circuit means the active condition for this input is low. When there is a bubble on the input, no input into the circuit is the same as a high on the inputs.

LOGIC DIAGRAMS

We are using the logic diagram in figure 4 to show how the NOT symbol can become a bubble on the output of another logic gate. Figure 4 shows two different logic diagrams. Both of the logic diagrams are identical in logic. The logic diagram can be drawn both ways, and usually the best way to draw it depends on the chips that are used. If the top drawing used an OR gate, which connected to another chip with the NOT gates in it, and the bottom drawing used a NOR gate, then both of the drawings would be appropriate.

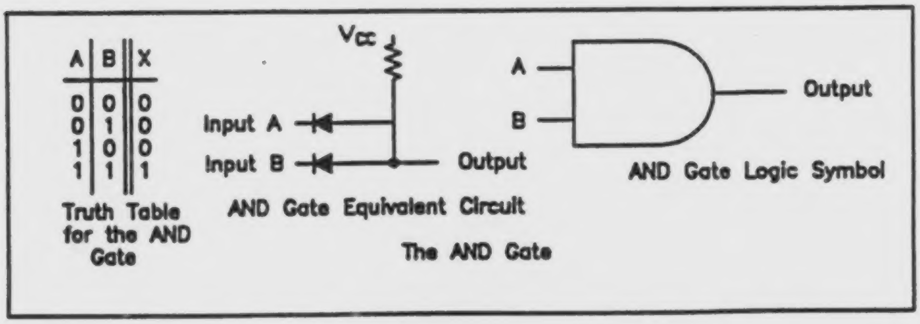
Notice that the truth table for this diagram shows that only one combination will result in the output going high. We can examine the circuit to determine why this is true. The reason for this logic is that there has to be 1s on the inputs to the AND gate to get a 1 on the output of the AND gate. The inverter after the OR gate will feed the AND gate 0s if either the A or B input is 1.


Input A
Input B
Output
OR Gate Equivalent Circuit
A
B
Output
OR Gate Logic Symbol

A	B	X
0	0	0
0	1	1
1	0	1
1	1	1

Truth Table for the OR Gate

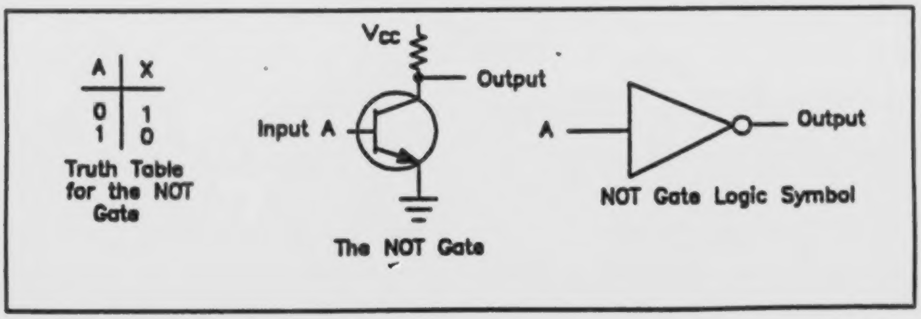
Figure 1


Vcc
Input A
Input B
Output
AND Gate Equivalent Circuit
A
B
Output
AND Gate Logic Symbol
The AND Gate

A	B	X
0	0	0
0	1	0
1	0	0
1	1	1

Truth Table for the AND Gate

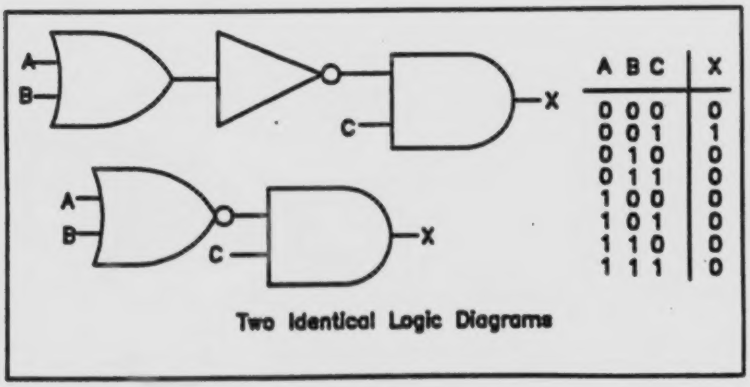
Figure 2


Vcc
Output
Input A
The NOT Gate
A
Output
NOT Gate Logic Symbol

A	X
0	1
1	0

Truth Table for the NOT Gate

Figure 3


A
B
C
X
A
B
C
X
Two Identical Logic Diagrams

A	B	C	X
0	0	0	0
0	0	1	1
0	1	0	0
0	1	1	0
1	0	0	0
1	0	1	0
1	1	0	0
1	1	1	0

Figure 4

Therefore, both the A and B inputs have to be 0 to get a 1 on the output. Then input C has to be a 1 or the output will go to 0.

Putting a bubble on the output of either an OR gate or an AND gate causes the name of the gate to change. We show the inverted output by putting the letter N in front of the name of the gate. This name change only refers to gates with the output inverted, not the input.

Figure 5 shows most of the combinations that you might see in any one gate. Any logic can be shown using these gates. Notice that the NOT gate is only the one with the bubble on the output. The buffer with the bubble on the input simply shows it to be a buffer with an inverting input or an active low input.

Understanding how the gates work is generally easier when we use 1s and 0s or the terms high and low. Actual circuits use voltage pulses or waveforms that provide the inputs and outputs for the gates.

Figure 6 shows the waveforms for the input and output for an AND gate and a NAND gate. If you pick a point on the waveforms and draw a vertical line straight down across the waveforms, you will be able to see the logic for that point in time. This is helpful in understanding how the waveforms affect the logic gates. You can convert the waveforms to 1s and 0s by using this method, and then evaluate the circuit.

If you examine the waveforms going into the AND gate and the NAND gate in figure 6, you will be able to see where the output waveforms come from. Notice that the input waveforms for both logic gates are the same. This results in the output waveforms for each logic gate being the inverse of each other. The difference between the gates is only the inverted output. The waveforms shown here resemble what you would see with an oscilloscope if you were probing the circuit.

EXERCISE: Read each question carefully, and take your time.

1. How can you include all possible inputs when making up a truth table?
   A. Include more inputs than what is required to avoid missing any.
   B. If you have a 1 and a 0 on each of the inputs at some point in the truth table, then you have covered all possible inputs.
   C. We do not usually include all inputs because there are too many of them.
   D. Make the inputs to the truth table by counting in binary.
   E. None of the above

2. What circuits would a NAND gate with its inputs tied together resemble?
   A. NOT gate
   B. AND gate
   C. OR gate
   D. NOR gate
   E. None of the above

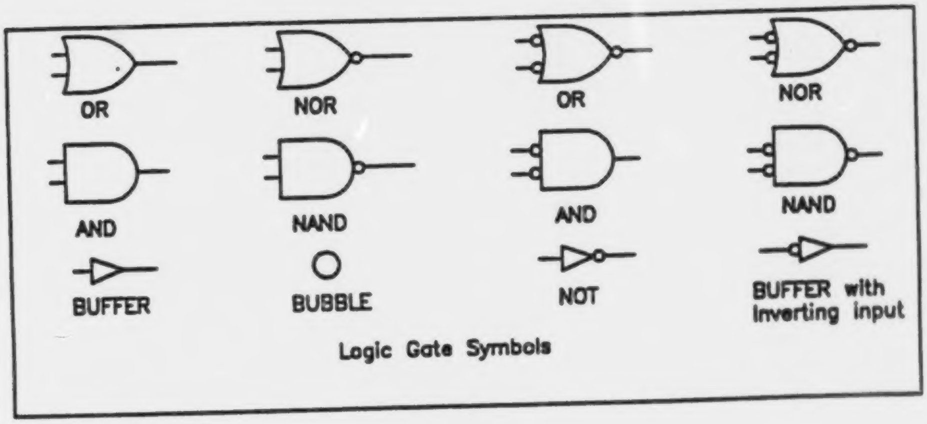

OR
NOR
OR
NOR
AND
NAND
AND
NAND
BUFFER
BUBBLE
NOT
BUFFER with Inverting input
Logic Gate Symbols

Figure 5

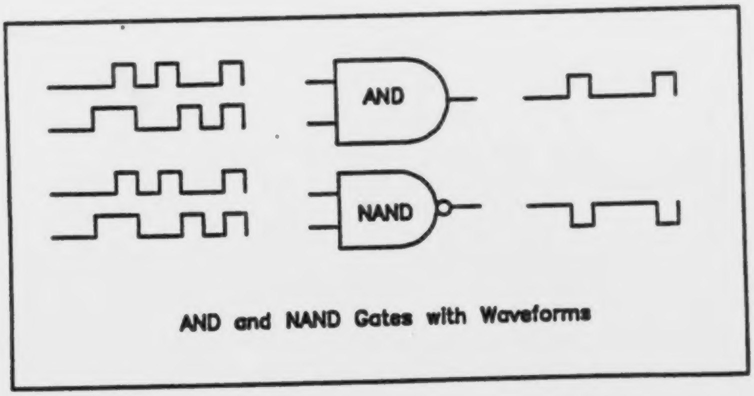

AND
NAND
AND and NAND Gates with Waveforms

Figure 6

3. If a digital waveform is fed into one input of a two-input NOR gate with the other input connected to ground, what will the output signal be?
   - A. The output will resemble the input.
   - B. The output will stay high.
   - C. The output will be a continuous 0.
   - D. The output will be the input waveform inverted.
   - E. None of the above

4. What do the bubbles mean when they are on the output of a large digital circuit?
   - A. The output will always be forced to 0.
   - B. The output is active low.
   - C. Only a 1 on the output will be considered an active output.
   - D. It means the output must have an open collector circuit.
   - E. None of the above

5. What would the output from a NAND gate be if we put a 0 on one input and fed the other input from a NOR gate with two inputs? One input of the NOR gate is receiving a pulsed input, and the other input is 0.
   - A. The output pulse inverted to the input pulse
   - B. Output pulse equal to the input pulse
   - C. Logic 0
   - D. Logic 1
   - E. None of the above

6. If you looked at a logic 1 of a TTL circuit on the oscilloscope, what would it look like?
   - A. Approximately 0 V
   - B. A series of pulses
   - C. A voltage of approximately 4 to 5 V
   - D. You cannot see logic.
   - E. None of the above

D-4

Boolean Algebra

UNIT OBJECTIVE: Upon completion of this instructional unit, the student will be able to demonstrate a knowledge of numbering systems with different bases, work with logic gates, understand logic diagrams, and be familiar with Boolean algebra.

SPECIFIC OBJECTIVES: Upon completion of this assignment, the student(s) will be able to demonstrate a knowledge of:

- how to simplify Boolean algebraic expressions
- how to draw logic diagrams for Boolean expressions

TERMS

DeMorgan's theorems: Important theorems that show how to use an OR gate with inverted inputs for an NAND gate

Boolean theorems: The rules governing Boolean algebra.

BOOLEAN SYMBOLS

If you have already completed your study of computer mathematics in advanced algebra and trigonometry classes, this lesson will be a review. Boolean algebra is in simpler than ordinary algebra. The difference between Boolean and ordinary algebra is in the numbering system each uses. Boolean algebra is based on the binary system which is just 1s and 0s. Ordinary algebra uses the decimal system with ten different digits.

The variable in Boolean algebra can only be equal to 1 or 0. When we write a Boolean expression, we are writing it for some specific point in the circuit. The logic level at that point in the circuit can only be a voltage close to either 5 V or 0 V.

It is customary to use the capital letters at the beginning of the alphabet to label the inputs to digital circuits. The letters toward the end of the alphabet are used to label the outputs. We will generally use X for the output of our logic circuit examples.

Figure 1 shows the logic gates, with the Boolean formula above each gate and the name of each gate below it. Notice the line across the top of some of the letters. This is called an *overbar*, and it indicates inversion. The prime symbol also indicates inversion. We will use the prime symbol in the following assignments because it is difficult to print the overbar.

Notice these examples:

$A' = \overline{A}$ *Example 1*

$A' + B' = \overline{A} + \overline{B}$ *Example 2*

$(A + B)' = \overline{A + B}$ *Example 3*

Example 1 shows that the overbar and the prime symbol mean the same thing. Example 2 shows how this would be used in a Boolean formula. Example 3 shows how the parentheses will change the effect of the prime symbol. When the prime symbol follows a parenthesis, the entire expression within parentheses is inverted. If two areas are exactly covered by the same inversion, they will cancel each other out.

RULES FOR BOOLEAN ALGEBRA

Notice the rules listed below. These are the rules for Boolean algebra. We have underlined the Boolean rules that are different from the rules for ordinary algebra.

AND	OR	NOT
$0 \cdot 0 = 0$	$0 + 0 = 0$	$1' = 0$
$0 \cdot 1 = 0$	$0 + 1 = 1$	$0' = 1$
$1 \cdot 0 = 0$	$1 + 0 = 1$	
$1 \cdot 1 = 1$	$1 + 1 = 1$	

Rule #1, Identity Law: $0 \cdot A = 0$; $0 + A = A$; $1 \cdot A = A$; $1 + A = 1$.

Rule #2, Commutative Law: $A + B = B + A$; $A \cdot B = B \cdot A$.

Rule #3, Associative Law: $A + (B + C) = (A + B) + C$; $A(BC) = (AB)C$.

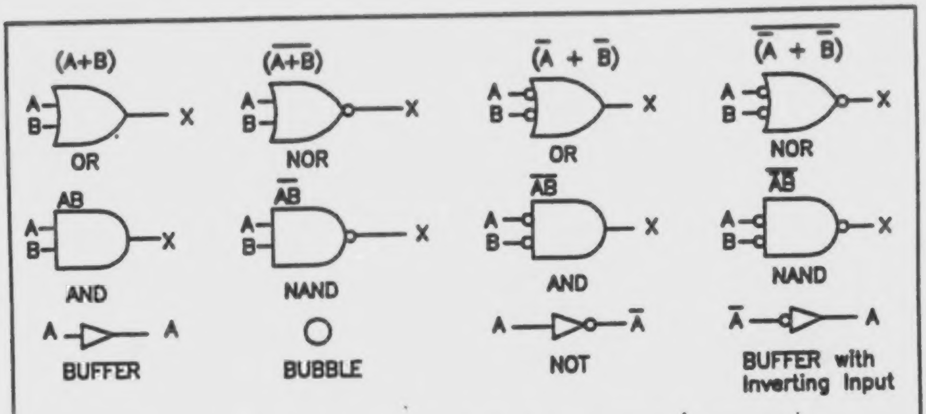
Rule #4, Distributive Law: $A(B + C) = AB + AC$; $\underline{A + BC = (A + B)(A + C)}$

Rule #5, Absorption Law: $\underline{A + AB = A;}$ $\underline{A(A + B) = A;}$ $\underline{A + A'B = A + B.}$

Rule #6, Complementary Law: $\underline{A + A' = 1}$; $\underline{AA' = 0.}$

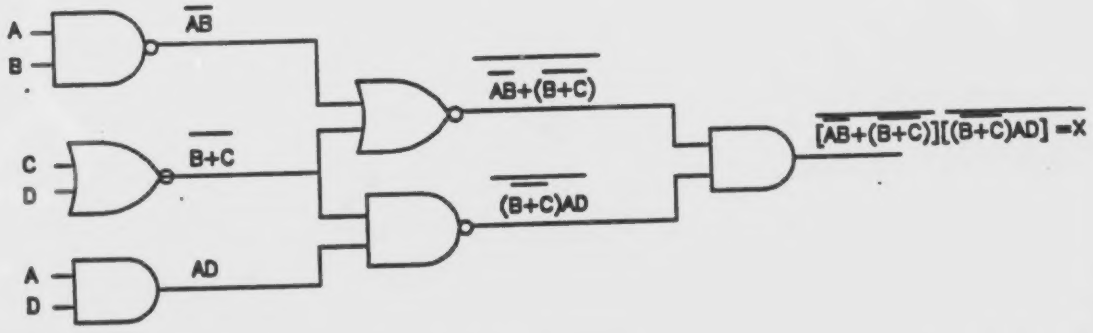
Rule #7, Indempotence Law: $\underline{A + A = A}$; $\underline{AA = A.}$

Rule #8, DeMorgan's Theorem: $\underline{(A + B)' = A'B'}$; $\underline{(AB)' = A' + B'.}$


$(A+B)$
A
B
X
OR
$(\overline{A+B})$
A
B
X
NOR
$(\overline{A} + \overline{B})$
A
B
X
OR
$\overline{(\overline{A} + \overline{B})}$
A
B
X
NOR
AB
A
B
X
AND
$\overline{AB}$
A
B
X
NAND
$\overline{AB}$
A
B
X
AND
$\overline{\overline{AB}}$
A
B
X
NAND
A
A
BUFFER
BUBBLE
A
$\overline{A}$
NOT
$\overline{A}$
A
BUFFER with Inverting Input

Logic Gate Symbols with their Boolean Algebraic Formulas

Figure 1


A
B
$\overline{AB}$
C
D
$\overline{B+C}$
A
D
AD
$\overline{\overline{AB}+(\overline{B+C})}$
$\overline{(\overline{B+C})AD}$
$[\overline{\overline{AB}+(\overline{B+C})}][\overline{(\overline{B+C})AD}] = X$

Complex Logic Diagram

Figure 2

You will notice that we have used a centered dot between variables to indicate multiplication. Using a dot instead of the letter X, for multiplication, will reduce the confusion caused by using the letter X for both multiplication and as a variable.

The unique rules for Boolean algebra are the result of dealing only with 1s and 0s. To see what happens, let's examine the complementary law. If we let A equal 1, then A' must equal 0. Multiplying 1 times 0 will always equal 0, and adding 1 to 0 always equals 1. These answers are only valid when we use binary mathematics for the computations.

This uniqueness also shows up in the indempotence law. If we let A equal 1 and we add 1 plus 1, then the output will be 1 not 2. The binary system does not have the number 2. Our formulas are calculating the logic at some specific point in a circuit. This point will be either high or low, and in this case it will be high or a logic 1.

SOLVING LOGIC DIAGRAMS

The AND and OR gates with the inverter to make the NAND and NOR gates can be used to make any logic circuit. Figure 2 shows a logic diagram with three columns of logic devices. Notice how the Boolean algebraic expression follows each gate. This is the expression for that point in the circuit. As we move through the logic diagram, the complex algebraic expressions can be taken like a simple letter and put into the next expression.

To see how this works, we start with the NAND gate at the top left. The inputs are A and B, and the output is $(AB)'$. This $(AB)'$ is then fed into the NOR gate which follows it in the second column. If the two inputs to the NOR gate in the second column were just A and B, then the output would be $(A+B)'$. The inputs are not just A and B, but the outputs from the NAND gate and NOR gates in the first column.

The NOR gate in the second column takes these two complex inputs, and its output is the result of adding them as we show in the diagram. The output from the AND gate, which is combining the inputs from the second column, looks complex.

Remember the rule in electronic circuits that complex circuits are nothing more than a collection of simple circuits. This rule also applies to these formulas. The final formula is simply the combination of the simpler formulas.

DRAWING LOGIC DIAGRAMS

Now to reverse the process and take the Boolean algebraic formula and draw the logic diagram involves the same techniques. We can start by using the formula from figure 2.

$$X = [(AB)'+(B+C)']' \; [(B+C)'AD]'$$

We start by separating the formula into its basic parts. It is easier to start from the left side of the formula. Notice that the first gate that we can see is the NAND gate $(AB)'$. We draw the NAND gate in the first column. The plus sign and prime symbol tells us that the NAND gate is NORed with another NOR gate. We would draw this NOR gate that shows in the formula as $(A+B)'$ under the NAND gate that we just drew. Next, we can see that the combination of gates is

ANDed with another combination. The first gate in the next combination is the same gate that we just drew. We don't need to draw it again. Moving on a little farther we see the AND gate which is feeding the NAND along with our NOR gate. We draw the AND gate. We now have our first column of gates, which are the basic gates in the formula.

Within the brackets are two more gates, which we would draw in the second column. Be sure when you are drawing these gates to keep the columns straight, one gate under the next, and to leave room to write formulas after the gates. In the first set of brackets we see a plus sign and that a prime symbol covers the whole bracket. This means the two gates in the first column are fed into a NOR gate. We draw a NOR gate in our second column. Then moving to the second set of brackets, we see that the two gates are multiplied together with a prime symbol there too. This indicates a NAND gate, which we draw under the NOR gate in the second column. Looking again at the formula, we see that the two sets of brackets are joined by an AND gate, which we put in the third column. When a logic diagram like this is drawn, it will help to put the formulas, as we have done in figure 2, on the drawing after each gate.

Take some scrap paper, and try drawing the logic diagram for the following formula.

$$X = [AB(C+A)']'+(C+A)'+(B+C)$$

When you have finished drawing the logic diagram, compare it with figure 3. Do not look at figure 3 until you have finished your drawing.

SIMPLIFYING BOOLEAN FORMULAS

Boolean algebra is easier to simplify and work with than ordinary algebra. As you will remember, Boolean algebra only deals with 1s and 0s. Examine the list of Boolean rules that we gave you. Now let's use these rules to simplify the following formula.

$$X = [A'+(A+B)]'$$

The A' times the terms in the parentheses with the prime symbol covering the whole thing is a NOR gate. We can change this NOR gate by using DeMorgan's theorem. Notice that the prime symbol has gone because we ended up with a double inversion over the A.

$$X = A\cdot(A+B)'$$

Next we can change the $(A+B)'$ portion of the formula to $A'B'$. This will give us the following.

$$X = A\cdot(A'B')$$

The formula now shows us that we are multiplying A times A'. The complementary law says this is equal to 0. The 0 ANDed or multiplied by the B' will also equal 0 according to the identity law. This reduces the formula to $X = 0$.

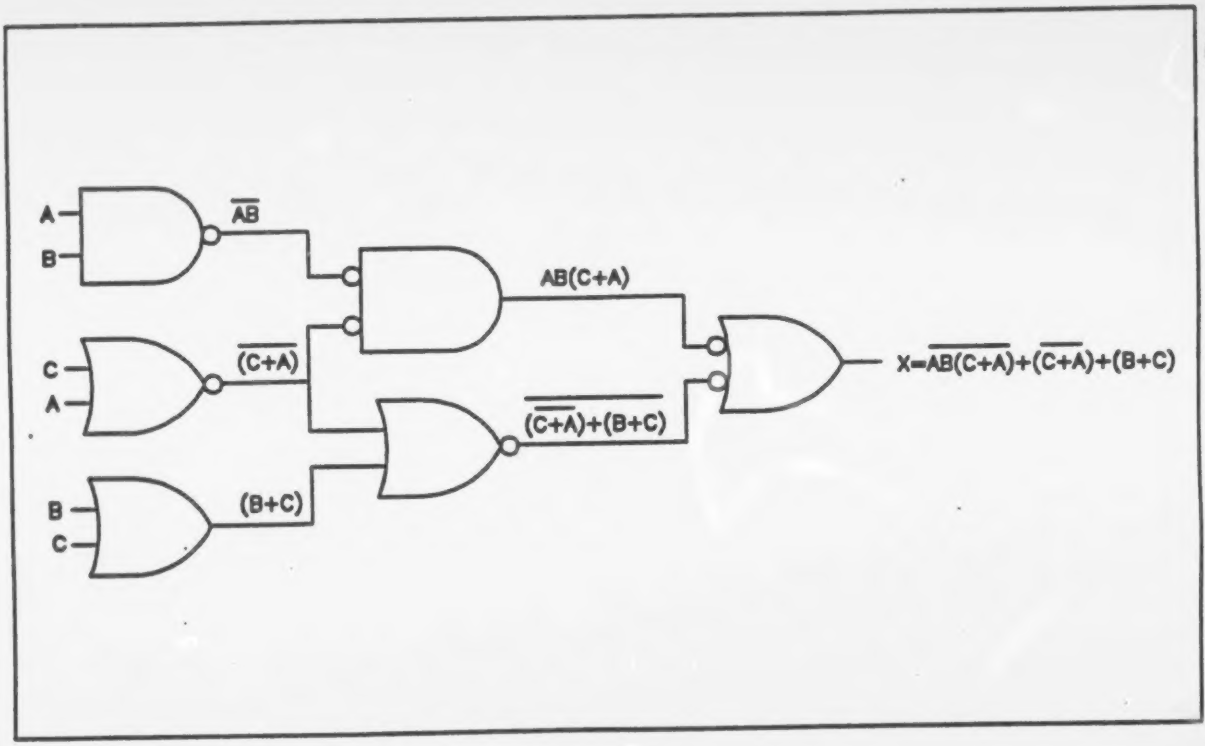

A
B
$\overline{AB}$
C
A
$(\overline{C+A})$
B
C
$(B+C)$
$AB(C+A)$
$\overline{(\overline{C+A})+(B+C)}$
$X=\overline{AB(C+A)}+(\overline{C+A})+(B+C)$

Figure 3

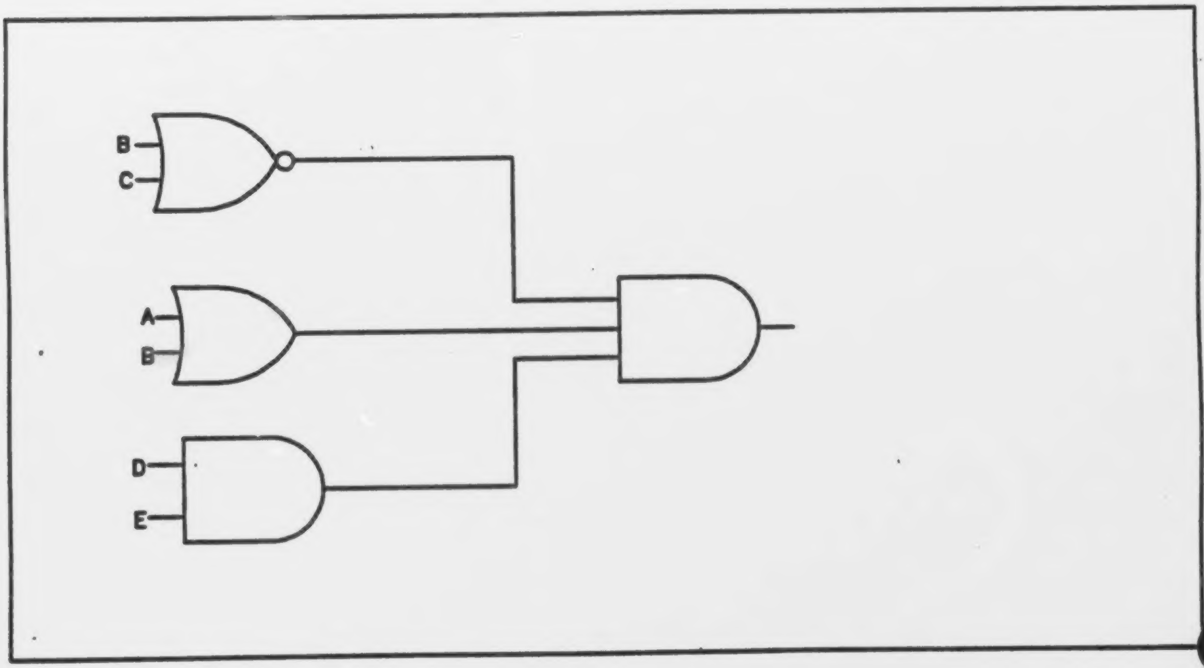


Figure 4

Let's look at another formula. The following formula shows two complex terms in parentheses. Without reading any further, copy this formula down on a piece of scrap paper, refer to the rules listed earlier, and see if you can simplify it.

$$X = (A+A'B)(A'B')$$

To start simplifying this formula, we would examine the first term and look for some way to change or reduce it. Looking through the list of rules concerning Boolean algebra, we find the absorption law. Using the absorption law, we can change the $A+A'B$ term into $(A+B)$.

Next, DeMorgan's theorem will allow us to change the second term $A'B'$ into $(A+B)'$. Now we can write these two terms as follows.

$$X = (A+B)(A+B)'$$

Notice that we have two complex terms that are the same except for the prime symbol. These two terms are similar to AA'. The term AA' will equal 0 according to the complementary law. As a result the formula now reduces to:

$$X = 0$$

EXERCISE: Read each question carefully, and take your time. Use your notebook paper or scrap paper to solve the problems.

1. Use the rules for Boolean algebra to simplify the Boolean expression, $X = (B+BC)+B'$.
   A. $X = B$
   B. $X = 0$
   C. $X = 1$
   D. $X = BC'$
   E. None of the above

2. Use the rules for Boolean algebra to simplify the Boolean expression, $X = (A+BC)(A'C')$.
   A. $X = 1$
   B. $X = AC'$
   C. $X = B$
   D. $X = 0$
   E. None of the above

3. Select the correct Boolean expression for the logic diagram in figure 4.
   A. $X = (B+C)(A+B)'DE$
   B. $X = (B+C)'(A+B)DE$
   C. $X = (B+C)'(A+B)D'E$
   D. $X = (A+B)DE$

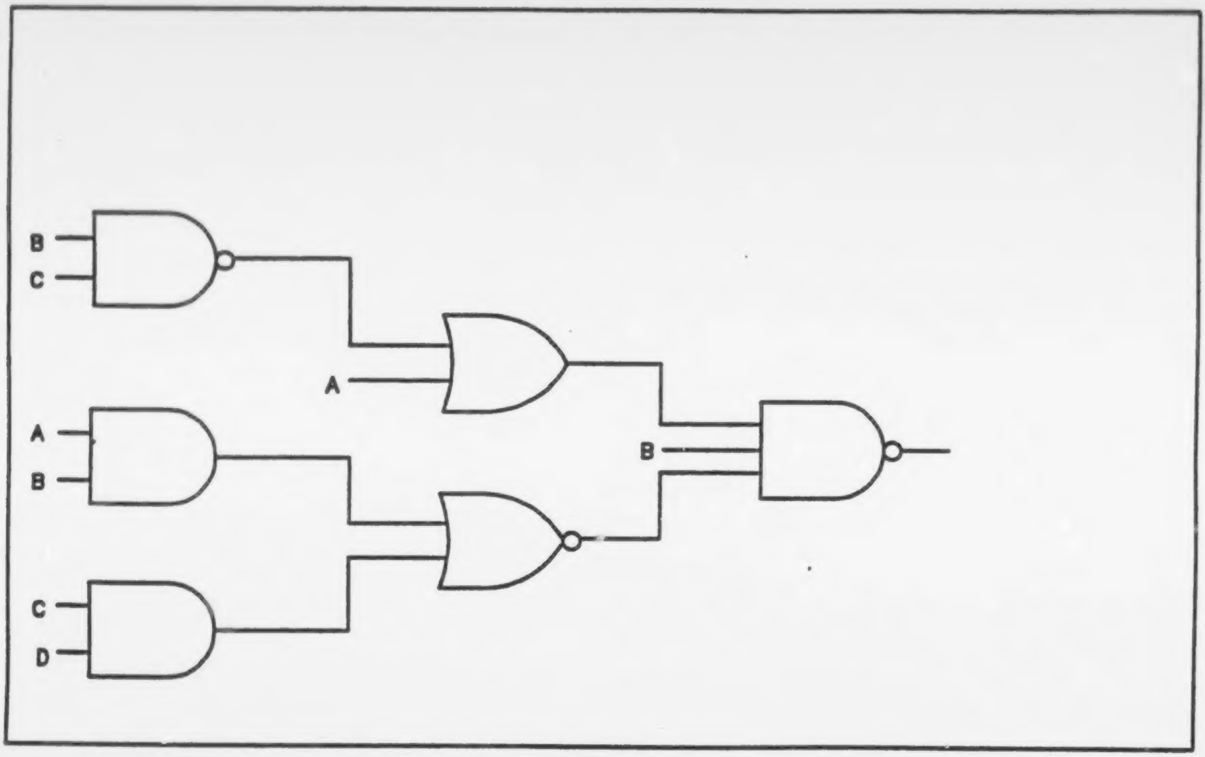


Figure 5

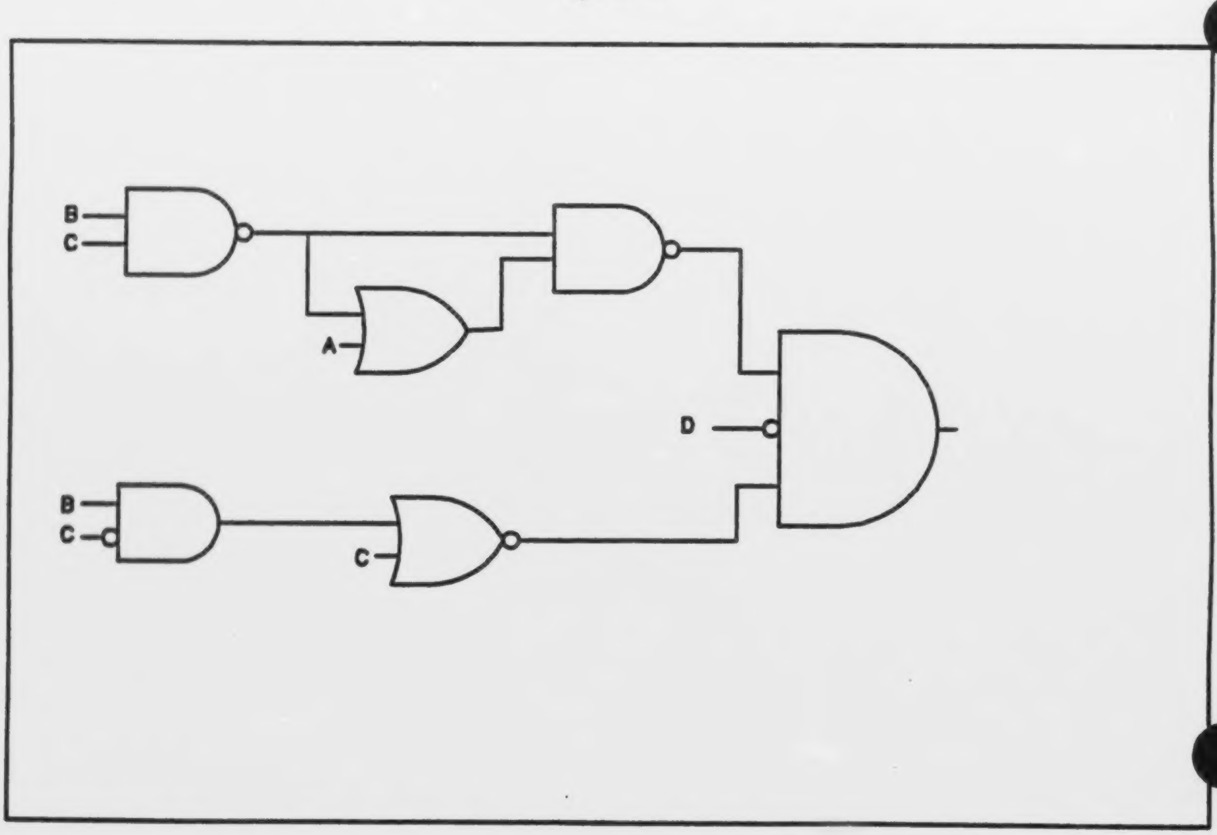


Figure 6

E. None of the above.

4. Select the correct Boolean expression for the logic diagram in figure 5.
   A. $X = \{[BC+A](AB+CD)'B\}'$
   B. $X = [(BC)'(AB+CD)'B]'$
   C. $X = \{[(BC)'+A](AB+CD)'B\}'$
   D. $X = [(BC)'+A](AB+CD)'$
   E. None of the above.

5. Select the correct Boolean expression for the logic diagram in figure 6.
   A. $X = \{B'[A+(BC)']\}'(BD'+C)'D'$
   B. $X = \{(BC)'[A+(BC)']\}'(BD'+C)'$
   C. $X = (BC)'[A+(BC)'](BD'+C)'D'$
   D. $X = \{(BC)'[A+(BC)']\}'(BD'+C)'D'$
   E. None of the above.

D-5

XOR and XNOR

UNIT OBJECTIVE: Upon completion of this instructional unit, the student will be able to demonstrate a knowledge of numbering systems with different bases, work with logic gates, understand logic diagrams, and be familiar with Boolean algebra.

SPECIFIC OBJECTIVES: Upon completion of this assignment, the student(s) will be able to demonstrate a knowledge of:

- the XOR and XNOR gates
- the difference between TTL outputs and tristate

TERMS

Totem pole output: This output is similar to the push-pull class B output used in the audio output of many linear circuits. It is faster than other outputs used in digital circuits.

Bus contention: When two or more totem pole outputs are in parallel, they will result in an invalid output if they are not all high or low at the same time. This problem is solved by adding additional circuitry. When this additional circuitry fails or the timing is off, then the problem called bus contention occurs.

EXCLUSIVE GATES

One of the digital circuits that has been used often has been put into its own IC and given a separate symbol like any other logic gate. This circuit is called the *Exclusive OR* gate, and the inverse of this gate is the *Exclusive NOR*. They are normally shown as XOR and XNOR.

Figure 1 shows the equivalent circuit, or the circuit as it was, and the logic symbols for XOR and XNOR. The equivalent circuit, as you can see, consists of two AND gates, two inverters, and one OR gate.

Your mathematics courses will help you understand these circuits. The value of this circuit is in its logic. Look at the truth table, and you will notice that the XOR circuit only goes high when the inputs are different. We can invert this in the XNOR and have the circuit go high only when the inputs are the same. This is valuable for making circuits to compare data.

We have included the Boolean formula for each of the exclusive circuits as shown. When you are simplifying a Boolean expression, it helps to watch for an arrangement of terms that would allow the use of an exclusive gate. Note also that the logic requires that these circuits have only two inputs. There are no exclusive gates with a different number of inputs than two.

One common use for the XOR gates is in comparing data. Remember that their logic depends on the input being the same or different.

Examine the circuit in figure 2. Notice that there are four inputs to the two XOR gates. The top two inputs, labeled A_1 and A_0, go to different XOR gates, just as the B inputs go to different XOR gates. This allows the data to be compared by the two XOR gates, and then the information will be combined in the AND gate that follows. Actually, we have XNOR gates with the inverters following the XOR gates.

If we put the number 10_2 on both the A and B inputs, we can examine the circuit and see what happens. The 10_2 on both inputs results in an 11_2 on the top XOR and 00_2 on the bottom XOR gate. Now when the inputs are the same on an XOR gate, the output goes low which is inverted and fed as 1s to the AND gate. This results in a 1 on the output of this circuit.

Let's try two different numbers on the inputs to this circuit: a 10_2 for the A inputs and 11_2 for the B inputs. Now the bottom XOR gate has different inputs while the top XOR gate has the same inputs. We end up with a 1 and a 0 on the input to the AND gate and a 0 on the output. This circuit will come up with a 1 on its output when the two numbers are the same and a 0 when they are not.

DIGITAL IC SPECIFICATIONS

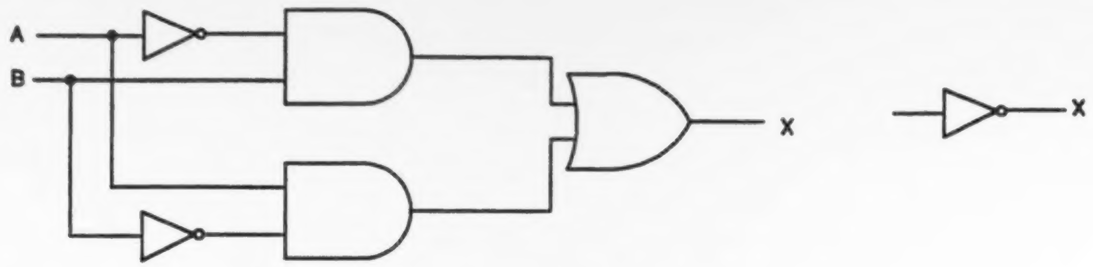
The industry has set standards for the voltage levels of digital ICs. The digital ICs, which are composed of bipolar transistors called TTL for transistor transistor logic, have standard voltage levels for their inputs and outputs. The industry has set up standard designations for these voltages: V_{OH} for voltage output high, V_{IH} for voltage input high, V_{OL} for voltage output low, and V_{IL} for voltage input low. The industry standard voltages that manufacturers usually specify for their TTL ICs are as follows;

Parameter	Min V	Typical V	Max V
V_{IH}	2.0	-	-
V_{IL}	-	-	0.8
V_{OH}	2.4	3.6	-
V_{OL}	-	0.2	0.4

These voltages are based on the supply voltage, V_{CC}, of 5 V. Notice that the minimum output voltage, V_{OH}, which is a valid high, is 2.4 V. Also notice that the minimum input high, V_{IH}, is 2.0 V. If the circuitry is operating under these minimum conditions, there is 0.4 V difference between the output of the circuit feeding and the input of the circuit receiving.

This means that for noise to cause a false reading, based on the manufacturer's minimum specifications, the noise pulse must be at least 0.4 V high. The voltage separation on the low side is also 0.4 V.

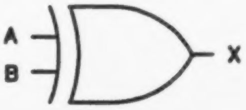
Circuit designers are often concerned about the length of time it will take a pulse to travel through the circuit. To be able to calculate the delay that a pulse may have requires a knowledge of the propagation delay of the individual gates. The *propagation delay* is defined as the time delay



Equivalent Circuit

Truth Table

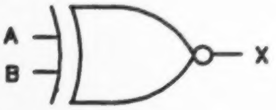
A	B	X	$\overline{X}$
0	0	0	1
0	1	1	0
1	0	1	0
1	1	0	1



XOR

Formula for XOR

$X=\overline{A}B+A\overline{B}$



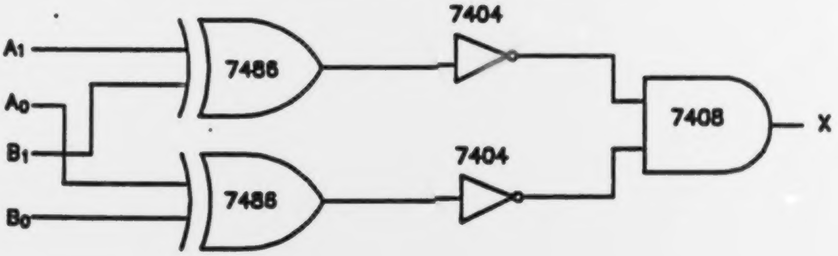
XNOR

Formula for XNOR

$X=\overline{\overline{A}B+A\overline{B}}$

XOR and XNOR Equivalent Circuits, Symbols and Truth Table

Figure 1


7404
A1
7486
A0
7408
X
B1
7404
7486
B0

This Circuit Will Test for the Equality of Two Bit Numbers

Figure 2

between the input signal and the change in the output. This propagation delay can be different for the same circuit between going from a low to a high and from a high to a low.

The ability of a circuit to feed a signal to many other circuits is also important. This ability is called the fan out. The *fan out* is the number of standard inputs that can be reliably driven by the output.

Manufacturers also build their circuits with inputs that are not standard. The input of a digital circuit can be a fraction of one standard input or equal to more than one standard input.

DIGITAL IC INTERNAL CIRCUITRY

The TTL (transistor transistor logic) is still widely used for making logic circuits. The various MOS (metal oxide semiconductor) devices are becoming more popular and are replacing the TTL devices in a lot of applications. We have used the TTL circuitry in the discussions that follow. There is little difference between the circuitry for the TTL and that for the MOS devices in the areas that we will cover.

The circuitry in figure 2 represents the circuitry you would find in a typical TTL NAND gate. Notice that the input is feeding into the emitters of the transistor Q_1. Unlike discrete components, ICs often have transistors with multiple emitters. Designers can do a lot of things in ICs that would be difficult in individual components. As you examine the circuit, you will notice that the status of transistor Q_2 controls the output of the circuit. Remember how the class B push-pull circuitry works. This output circuitry is called totem pole circuitry. The totem pole circuitry on the output of this NAND gate is very similar to push-pull circuitry.

The primary difference between the push-pull circuitry and the totem pole output circuitry is that the totem pole uses both NPN transistors. Remember that the push-pull had the output feeding from the emitters of both transistors. Here the output comes from the emitter of one and the collector of the other transistor.

This totem pole output will have either the top transistor turned on or the bottom transistor turned on, but not both at the same time. A big advantage to this type of circuitry is its speed. This type of circuit is faster than most of the other outputs. Designers are always trying to increase the speed at which a digital circuit switches.

If you will look at the output circuitry in figure 3, you will notice that it is an open collector. To get a high on the output, it is necessary to add a pull up resistor to the circuit. A pull-up resistor is a resistor from V_{CC} to the collector of the internal transistor or the output of the IC.

When the transistor is turned off or in the open condition, the voltage from V_{CC} will be on the output. When you are picking a value for the pull-up resistor, it is important to pick a value that will allow sufficient current to drive the input circuitry. The input circuitry will have a certain amount of capacitance. The open collector output should be able to quickly charge this capacitance in the input circuitry.

If you run too much current by picking a value for the pull-up resistor that is too small, you will cause the internal transistor to slow its switching time. A transistor will switch faster if it is out of saturation. Larger amounts of current require more switching time.

The one big advantage this circuit has over the totem pole circuit is that this circuit can be operated in parallel with other open collector output circuits. When a group of open collector circuits have their outputs in parallel, one output going low will take the common output low. The open collector outputs must all be high before the output will go high.

This logic is the same as an AND gate, and must be considered when you are trying to put a circuit together. To help you understand the problem of having digital outputs in parallel, we have drawn two totem pole circuits in parallel, in figure 4. Notice the line with the arrows showing the current flow. The circuit on the left is shown with its output high and the circuit on the right has its output low. This causes the current from the left totem pole circuit to go out and then back into the output of the totem pole circuit on the right. The collector resistors in the output circuitry will usually protect the circuits from any damage as a result of this circuit short.

With the two outputs in parallel, the output voltage will not be correct. The output voltage cannot be a valid high or low but will end up midway between V_{CC} and ground. This problem of parallel totem pole outputs is called *bus contention.*

If you were talking to an electrician, he or she would describe a bus as a heavy electrical wire designed to carry large amounts of current. The term *bus* is used in a similar manner for digital electronics, except that, instead of current, it will carry a lot of information or data. The *bus line* refers to a group of lines that will carry data or information in the computer.

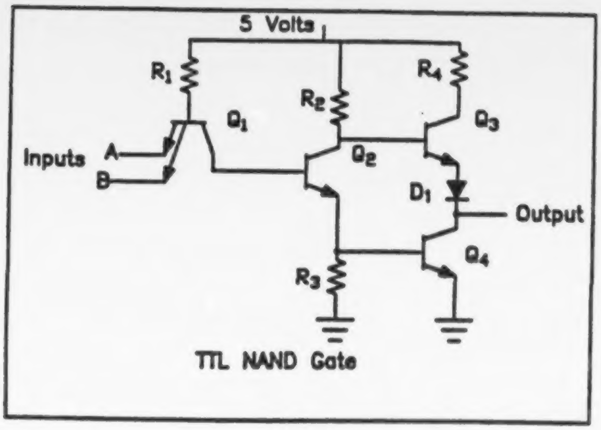
TRISTATE CIRCUITRY

As we mentioned earlier, the totem pole circuitry has a speed advantage over other types of output circuitry. This speed advantage is important enough to cause designers to figure out a way to continue using the totem pole circuitry and use it in parallel without the problem of bus contention. To solve the problem of bus contention, they have added additional circuitry. Figure 5 shows this additional circuitry added to the circuitry.

Notice that, in figure 6, instead of a NAND gate, we have an inverter. The enable line has become our other input. The enable line is not a logic input but is only used to control the device and disconnect it from the bus line. When the enable line is pulled low, the circuit is effectively disconnected from the bus line. By only allowing one output to be connected to the bus line at any time, we have eliminated the problem of totem pole circuits being in parallel.

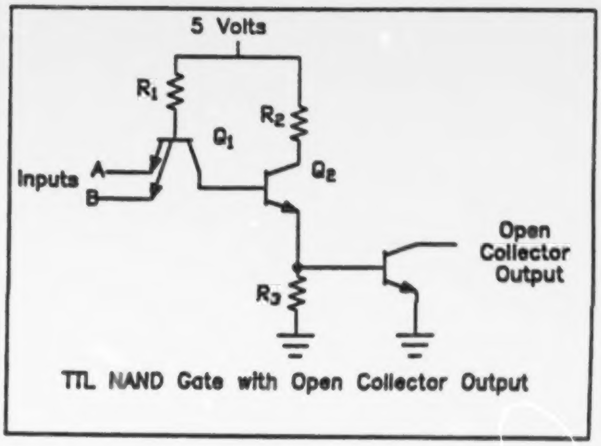
To see how this is done, let's start by examining what happens when a low is placed on the enable line. The low on the enable line causes the voltage on the base of Q_3 to go low, and the transistor then turns off. The enable circuitry puts the collector of Q_2 at 0, and the result is not enough current for the base of Q_4, which will also turn off. The final result is that both output transistors are turned off, which disconnects the output from the bus line.

The circuitry that controls the enable line will only turn on one totem pole output at a time. Bus contention will occur if the control circuitry fails. When bus contention occurs with MOS circuitry, the output resistance of each device is approximately 2 kΩ. This results in a voltage divider with the output at half of V_{CC}. The MOS devices are not usually hurt by this heavy flow of current. The only problem is a logic failure. The data is false and not transferred properly.


5 Volts
R1
R4
R2
Q1
Q3
Inputs
A
B
Q2
D1
Output
Q4
R3

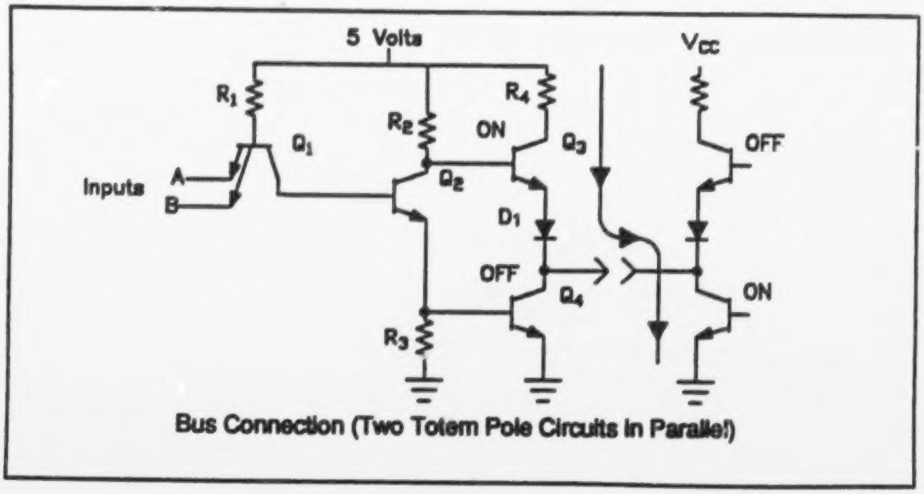
TTL NAND Gate

Figure 3


5 Volts
R1
R2
Q1
Inputs
A
B
Q2
Open Collector Output
R3

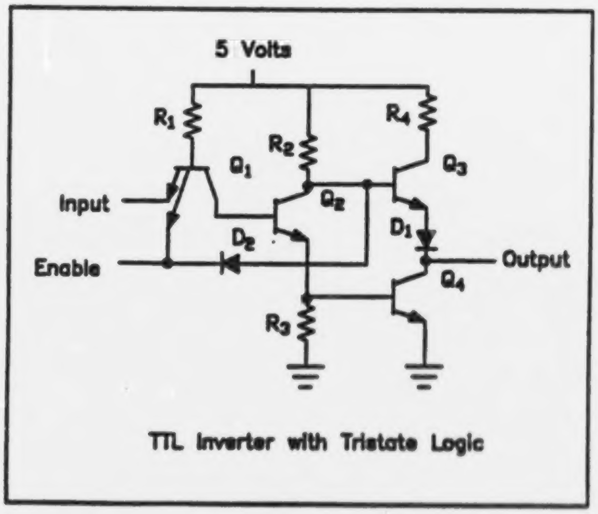
TTL NAND Gate with Open Collector Output

Figure 4


5 Volts
Vcc
R1
R4
R2
ON
Q1
Q3
OFF
Inputs
A
B
Q2
D1
OFF
Q4
ON
R3

Bus Connection (Two Totem Pole Circuits in Parallel)

Figure 5


5 Volts
R1
R4
R2
Q1
Q3
Input
Q2
D2
D1
Enable
Output
Q4
R3

TTL Inverter with Tristate Logic

Figure 6

TTL IDENTIFICATION

There are many different types of the basic TTL and MOS digital chips. Designers have changed different parts of the circuitry to improve certain characteristics. The TTL series with a lower power consumption is labeled with the letter L in the device number. For example, the 74L00 would be a low power device. They have done this by simply increasing the value of the resistors in the circuit. The 74H00 is a high-speed device with smaller resistors and the use of darlington circuitry. The H series has been replaced by the Schottky devices. The Schottky devices have the increase in speed without the major increase in power consumption.

The Schottky devices use Schottky diodes to keep the transistors from going into hard saturation. A transistor will switch faster if it has less current to switch. The diodes are connected between the collector and base so the collector voltage will not drop below the base voltage. The Schottky devices add an S to their label. The low power schottky includes the S and L, such as the 74LS00. The Schottky with the low power gives up some speed for the low power. The difference between a chip with just the S and one with the LS is that the resistance values have been increased in the low power version when compared with the straight Schottky version.

EXERCISE: Read each question carefully, and take your time. Use your notebook paper or scrap paper to solve the problems.

1. How many XOR gates would you need to build a circuit that would compare BCD numbers?
   A. 2
   B. 3
   C. 4
   D. 5
   E. None of the above

2. What is the maximum output voltage for a valid low from the output of a TTL circuit?
   A. 0.2 V
   B. 0.3 V
   C. 0.4 V
   D. 0.5 V
   E. None of the above

3. What is the minimum output voltage for a valid logic high on a TTL circuit?
   A. 2.2 V
   B. 2.4 V
   C. 2.6 V
   D. 2.8 V
   E. None of the above

4. What voltage will a noise pulse have to exceed to cause a problem in TTL circuits?
   A. 0.8 V
   B. 0.6 V
   C. 0.4 V
   D. 0.2 V
   E. None of the above

5. What does the term *fan out* mean?
   A. A unit of cooling necessary to keep the circuits from overheating
   B. The number of standard inputs that can be driven by an output
   C. The speed at which the output can drive the inputs
   D. If the fan out is low, bus contention may occur
   E. None of the above

6. What is the term used to describe the time starting from the receipt of a pulse on the input until the circuit switches on the output?
   A. Bus delay
   B. Tristate time
   C. Field delay
   D. Propagation delay
   E. None of the above

7. Which circuit is similar to the totem pole circuit?
   A. Class A amplifier output
   B. Class C circuit
   C. Class B push-pull circuit
   D. Tristate circuit
   E. None of the above

8. What is the advantage of using tristate logic on the output of some digital circuits?
   A. To increase the fan out
   B. To avoid bus contention
   C. A higher V_{CC} can be used
   D. The propagation delay is reduced.
   E. None of the above

9. What additional component must be added to an open collector output circuit?
   A. Filter capacitor
   B. Pull-up resistor
   C. Output diode
   D. A transistor
   E. None of the above

10. Why should the value of a pull-up resistor be kept high?
    A. To avoid overheating the internal transistor
    B. To reduce the circuit's current consumption
    C. To be sure the output will receive enough current
    D. To make the circuit switch faster
    E. None of the above

11. What do the letters L and S stand for in a 74LS00 IC?
    A. Low speed and Smart logic
    B. Low current and high Speed
    C. Less time and Short delay
    D. Lower cost and Stronger circuitry
    E. None of the above

12. What change do circuit designers make to reduce the current consumption in digital ICs?
    A. Add Schottky diodes
    B. Reduce the base current in the internal transistors
    C. Lower the V_{CC}
    D. Increase the resistance
    E. None of the above

Unit

E

Complex Digital Circuits

E-1: Flip-Flops
E-2: Registers I
E-3: Binary Addition
E-4: Decoders
E-5: Encoders and Multiplexers
E-6: One Shot and Schmitt Triggers
E-7: Interface with the Linear World
E-8: Data Transmission

E-1

Flip-Flops

UNIT OBJECTIVE: Upon completion of this instructional unit, the student will be able to demonstrate a knowledge of registers and adders and of circuits that convert analog to digital and transmit data.

SPECIFIC OBJECTIVES: Upon completion of this assignment, the student(s) will be able to demonstrate a knowledge of:

- how flip-flop is made
- how a flip-flop works

TERMS

Trailing edge: The part of a pulse that goes from a high to a low.

Asynchronous: An asynchronous circuit will change its output when there are changes in its input. A synchronous circuit will only change with clock pulses.

FLIP-FLOP

Your background from your mathematics courses will help you understand this assignment. Until now, you have been studying circuits with no memory function. If the input was removed, the output changed to reflect the lost input. The flip-flop circuit is one of the basic memory circuits that will hold its output when the input is removed.

The flip-flop (FF) is a combination of circuits that you are already familiar with. The flip-flop circuit is able to remember its output based on the input that once was there. Figure 1 shows how an FF circuit can be made using two NAND gates. Notice that their outputs are wired back to the inputs to form a circuit that will hold its output when the input is removed. The inputs to the circuit have been labeled *set* and *clear*. The outputs are Q and Q with an overbar. Remember that the overbar indicates that the logic is inverted.

We can examine how this circuit works by putting a 0 on the set input and a 1 on the clear input. The 0 on the set input will put that NAND gate's output to 1. The 1 from this NAND gate's output will then be on the input of the other NAND gate. Having a 1 on the clear input, which is the bottom NAND gate, will give a 0 on the output of this bottom NAND gate or a 0 on Q' (we say "Q not" for the Q'). The top NAND gate output, labeled Q, will have a logic 1, and the bottom NAND gate will have a logic 0.

Since this circuit has active low inputs, when we put a 1 or a high on both the set and clear inputs, we will have no change in the outputs. If we had used NOR gates instead of NAND gates, the inputs would be active high, and the no-change condition would be 0s on both inputs.

For a circuit using NOR gates, which is active high, putting 1s or a high on both inputs will create an error or invalid situation. The active low or NAND gate FF must have a high on both inputs during its resting condition or no-change condition. Then we can momentarily pulse the clear input low and clear the FF. This momentary low into the clear input will result in a 0 on the Q output and a 1 on the Q' output. The flip-flop will then remain in this condition until another low is received on the set input. Adding additional low pulses to the clear input will not cause any additional changes. Putting a low on the set input will set a 1 on the Q output, and the Q' output will then go to 0. The Q output is normally considered the output of an FF. To reduce the number of connections, some FFs will not use the Q' output.

Notice in figure 2 how the pulse inputs react with the set clear FF. The actual signal that drives an FF is not 1s and 0s but variations in the voltage that would look like this drawing. You can change this waveform to 1s and 0s for easier understanding by mentally drawing a vertical line at each change of the signal and noticing what the logic is going into the FF at that moment. Notice also how the outputs are the inverse of each other.

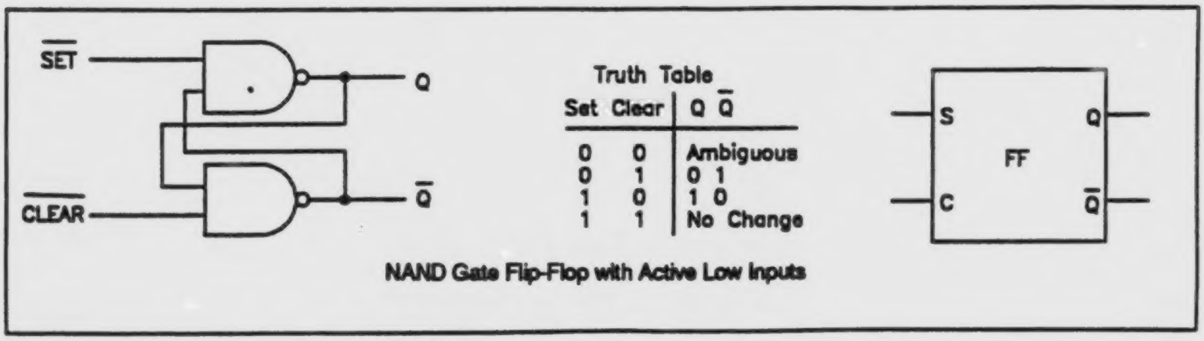
CLOCK-TRIGGERED FLIP-FLOP

The FF shown in figure 1 is a set clear flip-flop, which is an asynchronous circuit. An asynchronous circuit changes its output whenever the input changes. A synchronous circuit will only change its output when it receives a clock pulse. This type of circuit is synchronized to the clock pulses. Figure 3 shows a flip-flop that will change its output only with a clock pulse.

The NAND gates G1 and G2 have been added to the set clear FF in figure 1 to make figure 3. These NAND gates G1 and G2 are feeding the inputs to the set clear flip-flop. Notice that one of the inputs to each of the G1 and G2 NAND gates is connected to the output of the edge detector circuitry.

The edge detector circuitry will give a short spike on its output on either the positive or negative edge of the clock pulse. Notice the symbol for the flip-flop shown next to the circuit. It has a triangle at the clock input. The triangle is often used to show that the device is edge-triggered. If there were a bubble in front of the triangle, it would show that the FF would trigger on the negative or trailing edge of the clock pulse. The example in figure 3 will trigger on the positive or leading edge of the clock pulse.

If you will examine the circuit in figure 3, you will notice that in order to get a low out of either G1 or G2, there has to be a high coming from the edge detector. Remember that the NAND gate will only have a low on its output when it has all highs on its inputs. If a high pulse on the set input overlaps the leading edge of the clock, two highs will momentarily appear on the NAND gate G1. We will then get a low out of the NAND gate G1 and set the flip-flop. When the FF is set, there is a 1 or a high on the Q output.

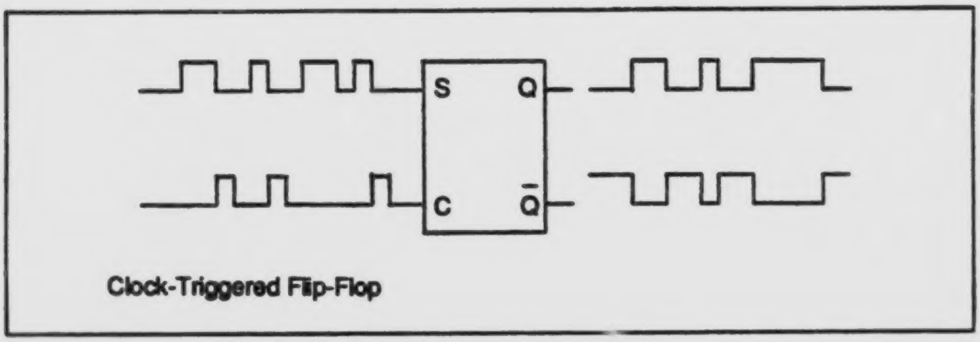

$\overline{SET}$
$\overline{CLEAR}$
Q
$\overline{Q}$
S
C
FF
Q
$\overline{Q}$

Truth Table

Set	Clear	Q $\overline{Q}$
0	0	Ambiguous
0	1	0 1
1	0	1 0
1	1	No Change

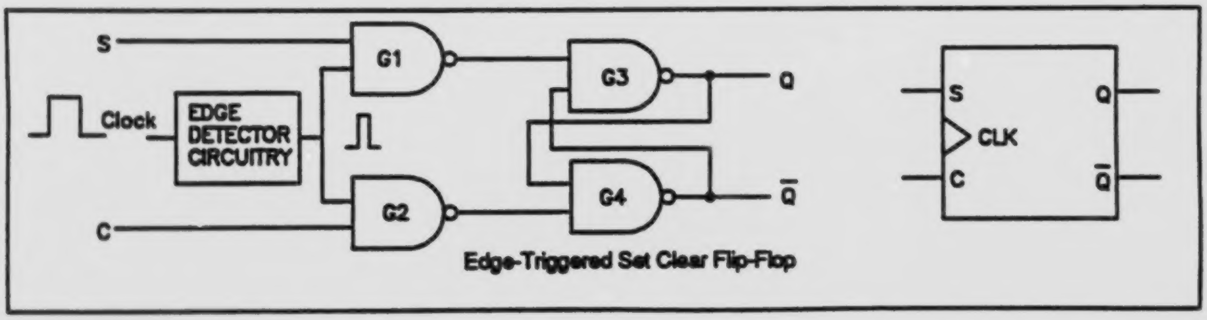
NAND Gate Flip-Flop with Active Low Inputs

Figure 1


S
C
Q
$\overline{Q}$

Clock-Triggered Flip-Flop

Figure 2


S
Clock
EDGE DETECTOR CIRCUITRY
C
G1
G2
G3
G4
Q
$\overline{Q}$
S
CLK
C
Q
$\overline{Q}$

Edge-Triggered Set Clear Flip-Flop

Figure 3

J-K AND D FLIP-FLOPS

By adding additional circuitry to the circuit in figure 3, we have been able to make the circuit in figure 4. Notice how the outputs of the circuit are fed back to the NAND gate inputs in parallel with the edge trigger. This flip-flop, called a ***J-K flip-flop***, is a common flip-flop and is very useful.

The logic for the J-K FF is similar to the logic for the circuit in figure 2. A high on the J input will result in a high on the Q output when it is triggered by a clock pulse. Putting a 1 on the K input will clear the Q output and result in a 1 on the Q' output. A 0 on both inputs will result in a no-change condition.

The difference between this J-K FF and the clocked, set clear FF in figure 3 happens when we put a high on both inputs of the J-K FF. Remember that highs on both inputs of an active low, clocked, set clear FF would be invalid or create an error. The result of putting highs on both inputs to a J-K FF will be toggling. The output is toggling when it switches its logic on every clock pulse.

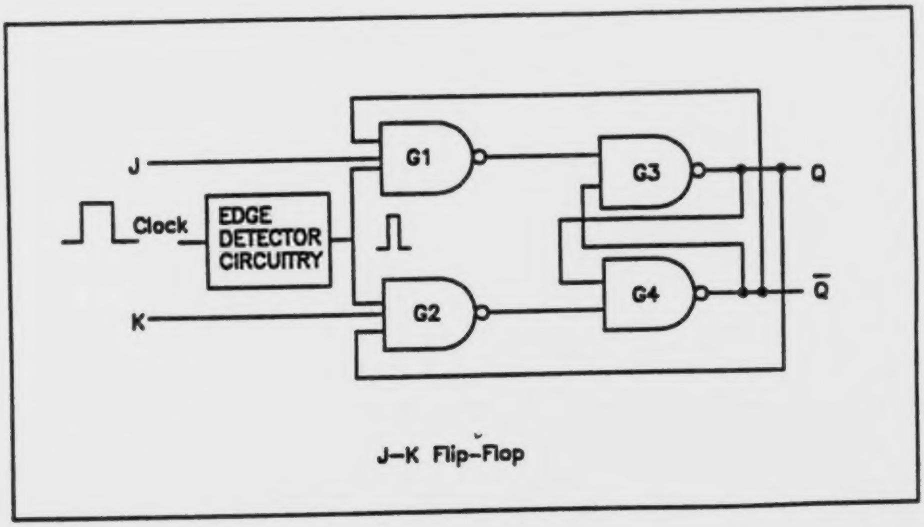
Let's examine figure 4 by starting with 1s on the J and K inputs. The Q output will be high or 1, and the Q' will be low or 0. The 1 on Q will result in a 1 on the input of G2, and the 0 on Q' will result in a 0 on G1. When the next clock pulse arrives, there will be a momentary 1 sent to both G1 and G2. Only G2 will have 1s on all three inputs during that clock pulse. This will result in G2 sending a low or 0 to G4 and switching the outputs, putting a 0 on Q and a 1 on Q'. The 1 on Q' will then put a 1 on G1 so it will send the low to G3 on the next clock pulse, causing the output to switch again. This output switching or toggling will continue for each clock pulse as long as the inputs have 1s on them.

The frequency of the output when a J-K FF is toggling is half the frequency of the input clock signal. Toggling FFs can be connected together to cut the frequency of the clock signal in half each time. This method of reducing the pulse rate is not used very often because the propagation delay in J-K flip-flops reduces the accuracy of the output timing.

Some J-K FFs have set and clear inputs as well as the J and K inputs. These set and clear inputs to gates G3 and G4 are brought out of the chip and labeled set and clear. The set and clear inputs will override the clock and the J and K inputs. When a signal is present on these inputs, the output changes immediately. Figure 5 shows the schematic symbol for a J-K FF with all of its inputs and outputs.

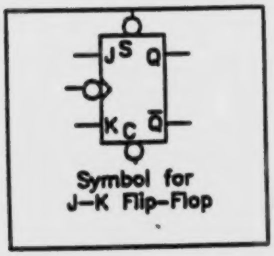
Notice on the symbol for a J-K FF that we show active low set and clear inputs, clock triggers on the trailing edge, J and K inputs, and two outputs. Each of the inputs and outputs on an FF requires a pin connection on the chip to access that input or output. The limited number of pins that can be put on a chip will reduce the number of FFs that can be put in the chip.

A 14-pin chip can hold only one J-K flip-flop, if all of the inputs and outputs must be connected to pins. We need two pins for V_{CC} and ground, and then the seven connections to the FF will result in 9 pins. There are not enough pins left for another 7-pin device. A 16-pin chip can hold two J-K flip-flops with all inputs and outputs. A lot of ICs are made with only one clock input to the chip. The set inputs may all be connected in common to one input pin and the clear inputs to another input pin. The exact arrangement may depend on the manufacturer's expected use for the chip.


J
Clock
EDGE
DETECTOR
CIRCUITRY
K
G1
G2
G3
G4
Q
$\overline{Q}$

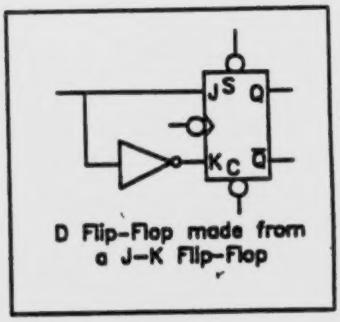
J-K Flip-Flop

Figure 4


J
S
Q
K
C
$\overline{Q}$

Symbol for
J-K Flip-Flop

Figure 5


J
S
Q
K
C
$\overline{Q}$

D Flip-Flop made from
a J-K Flip-Flop

Figure 6

If the toggling feature of a J-K flip flop is not needed, then the D flip-flop shown in figure 6 will eliminate the K input. In figure 6, a D FF is made from a J-K FF, because that is what the logic is, and not, necessarily, the arrangement of the internal transistors. The J input shown in figure 6 is usually labeled the D input on the symbol of a D flip-flop. Now with the D flip-flop with only a D input, clock input, and Q output, we only need 3 pins per FF. This will allow us to put four of these flip-flops into one 14-pin chip.

SPECIFICATIONS

The set and hold times are two important parameters for FFs. The *set time* is the amount of time that a valid signal must be on an input before the clock pulse hits. The *hold time* is the time that the signal pulse must remain on the input after the clock signal has hit.

We have discussed *propagation delay* before. This parameter is important for FFs. The additional circuitry in an FF results in a longer propagation delay and timing is often critical in an FF circuit. The propagation delay will be different between the output going high and going low. Also, by increasing the load, we find that the propagation delay will increase.

EXERCISE: Read each question carefully, and take your time. Use your notebook paper or scrap paper to solve the problems.

1. What will be on the Q output after 3 and 8 clock pulses for a J-K flip-flop that starts with a 1 on the Q output and is set up for toggling?
   A. 0, 0
   B. 0, 1
   C. 1, 0
   D. 1, 1
   E. None of the above

2. What logic will be on the Q output if a clock signal is coming into the set input of a set clear FF with active high inputs and the clear input is at 0?
   A. Inverted clock pulse
   B. Steady high
   C. Steady low
   D. Clock pulse
   E. None of the above

3. What logic has to be on all four inputs of a J-K FF for it to toggle? Assume that there is a continuous input of clock pulses.
   A. J and K are both low, and the set and clear are active.
   B. The J input has a 1 and the K a 0 with the set and clear inactive.
   C. The J and K are both high with the set high and clear low.
   D. The J and K are both high, and the set and clear are inactive.

E. None of the above

4. You have two J-K flip-flops set up for toggling, and the Q output of the first is connected to the clock input of the second. The frequency of the clock signal coming into the first is 100 Hz. What is the frequency of the signal coming from the second flip-flop's Q output?
   A. 200 Hz
   B. 100 Hz
   C. 50 Hz
   D. 25 Hz
   E. None of the above

5. What frequency would be on the Q output of a J-K flip-flop that was toggling if a clock signal with a period of 10 ms was fed into the clock input?
   A. 500 Hz
   B. 50 Hz
   C. 100 Hz
   D. 5 Hz
   E. None of the above

6. If a signal and the clock pulse were to arrive at an FF at exactly the same time, what parameter would tell us that the circuit will fail to give us a valid output?
   A. Hold
   B. Set
   C. Propagation delay
   D. Timing
   E. None of the above

E-2

Registers I

UNIT OBJECTIVE: Upon completion of this instructional unit, the student will be able to demonstrate a knowledge of registers and adders and of circuits that convert analog to digital and transmit data.

SPECIFIC OBJECTIVES: Upon completion of this assignment, the student(s) will be able to demonstrate a knowledge of:

- series and parallel input and output of data to a register
- the ripple counter and MOD numbers

TERMS

Ripple counter: This register is made with a J-K FF and has the outputs of each FF connected to the clock input of the following FF. This register will count up or down.

MOD number: The number of changes a ripple counter will go through. The MOD number can be changed by adding gates to clear it on a particular number.

DATA REGISTER

The flip-flop is not often used alone, but is usually made into a circuit with other FFs. We call a circuit made of FFs a *register*. As an example, to store a 4-bit word would require four FFs in a register. ***Your knowledge of mathematics from algebra and trigonometry classes will help you understand registers.*** Different methods are used to connect FFs to make registers; figure 1 shows the most common method.

When we try to examine the logic of a register, it helps to know what the logic on all the Q outputs is. If we assume that we have cleared the register, then we know that all Q outputs have a 0 on them. Notice that the clear inputs to all FFs are connected to one line, which shows to be the clear input to the chip. Notice also that all the clock inputs are connected and brought out to a common input.

Let's first examine this register by ignoring the set inputs and the NAND gates above them. We have cleared the register and put 0s on all the Q outputs. Let's assume that we have a signal that is pulsing into the D input with the data 1011_2. This signal is synchronized with the clock input. There should be one clock pulse for each bit of the 1011.

Notice the series input feeding into the first or D1 FF. Putting the 1011 into the register in series will take four clock pulses. The first bit, which is a 1 on the MSB end of the number, will

230

be on the D input of the D1 FF when the first clock pulse hits. This clock pulse hits all the FFs at the same time. Since all the Q outputs are 0, all the other FFs will get a 0 as their input. The first FF will see the 1 as its input. After a few nanoseconds for the propagation delay, the 1 will appear on the Q output of the first (D1) FF.

Now a 0 from the data appears on the first or D1 FF, and the Q output of the D1 FF has a 1 on it. This puts a 1 on the D input of the second (D2) FF. When the second clock pulse hits, the 0 from the input of the D1 FF is transferred to the Q output, and the 1 that was on the Q output of the D1 FF is transferred to the Q output of the D2 FF. So after the second clock pulse, we have a 0 on D1 and a 1 on D2 with 0s on D3 and D4.

Now the third and fourth clock pulses will continue moving the data in so that, at the end of the fourth clock pulse, there will be a 1 on the Q output of D1, a 1 on the Q output of D2, a 0 on the Q output of D3, and a 1 on the Q output of D4. Since we are feeding the number in from the left, the number is backwards on the page. If after the data is in, the series input goes to 0 and stays there, four more clock pulses will empty the register out the series output.

The data can be entered into this register much faster in parallel than in series. If we put the 1011 on the X inputs to the top left of the drawing and then pulse a high into the parallel transfer input, the data will immediately be put into the register. Another way to transfer the data to the register in parallel would be to use all AND gates and feed the output of the AND gates directly to the D inputs. When the clock pulse hits, the data would be transferred to the Q outputs. Notice that it takes only one clock pulse to transfer the data in, in parallel.

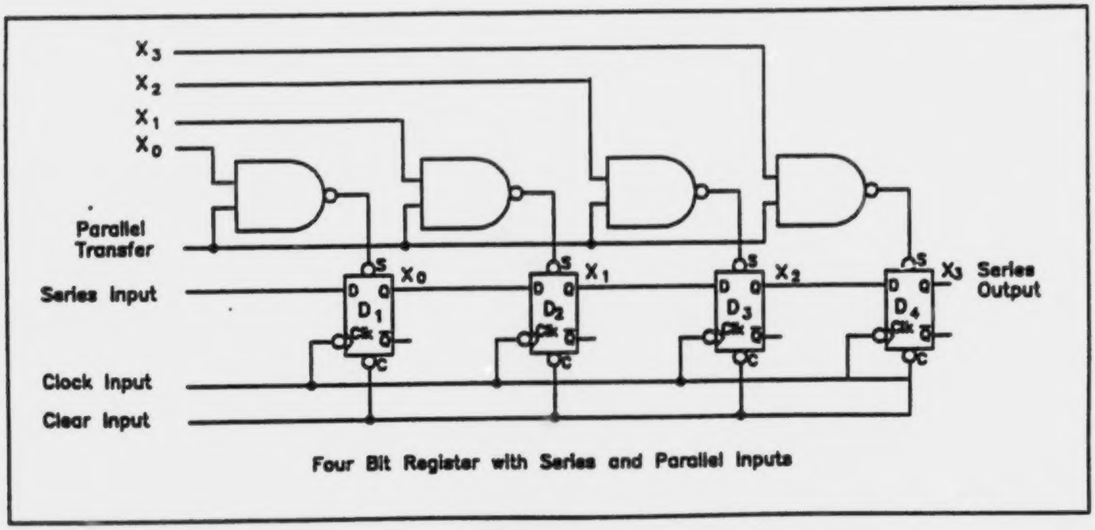
We can take the data out of the register in parallel by taking the data from the Q outputs. If we did not need to move the data in series, the Q outputs would not have to be connected to the next FF inputs. The circuit shown in figure 1 does not bring out the individual Q outputs, so we cannot take the data out in parallel.

RIPPLE COUNTER

We can use a register to count pulses. The register in figure 2 is a ripple counter, which will give a binary number that represents the number of pulses it has received. The propagation delay will not allow this counter to count very fast. We have drawn a 4-bit counter, which can count up to 15 or a binary 1111_2.

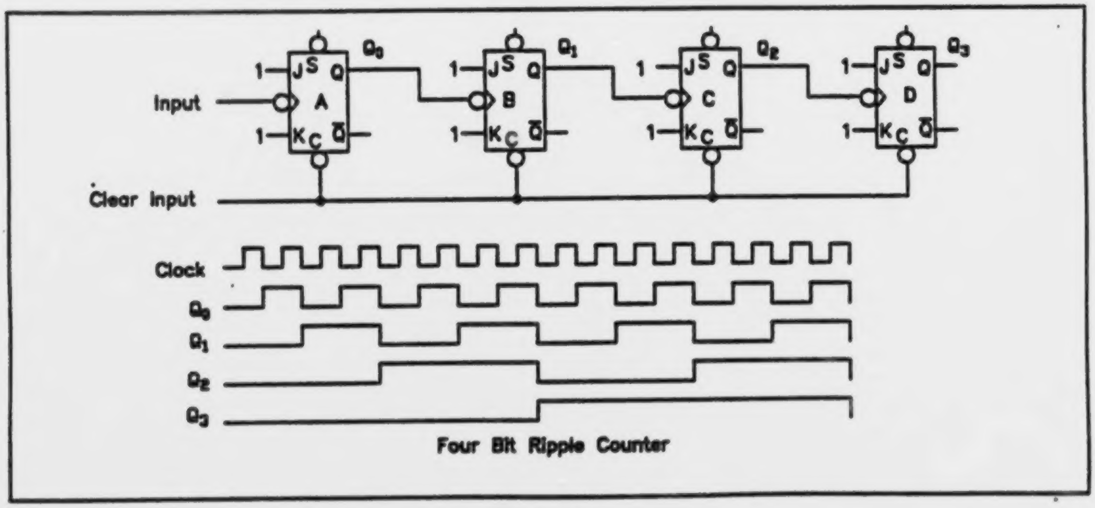
Notice that each of the FFs in the ripple counter has its J and K inputs set to 1 for toggling. The pulses that we are counting will enter into the clock input of the first FF (FF A). Before the first pulse, the register was cleared, and all Q outputs will start with 0 on them. Now, when the first pulse comes into the clock input of FF A, it will toggle, and the Q output will have a 1 on it. FF A holds the LSB of the count. When the second pulse hits, FF A will toggle again, putting a 0 on its Q output.

Each of these FFs will toggle on the trailing or negative edge of a pulse sent to its clock input. The Q output of each FF is connected to the clock input of the following FF. On the second pulse into FF A, the output went from a 1 to a 0, which is the trailing edge or negative part of the pulse. This would trigger the second FF, or FF B, to toggle and put a 1 on its Q output. With the second pulse now gone, we have a 0 in FF A and a 1 in FF B. This is the number 2 in binary. Remember, we are reading the number backwards on the page.


X3
X2
X1
X0
Parallel Transfer
Series Input
Clock Input
Clear Input
S
D
Q
D1
D2
D3
D4
Clk
Q̄
C
X0
X1
X2
X3
Series Output

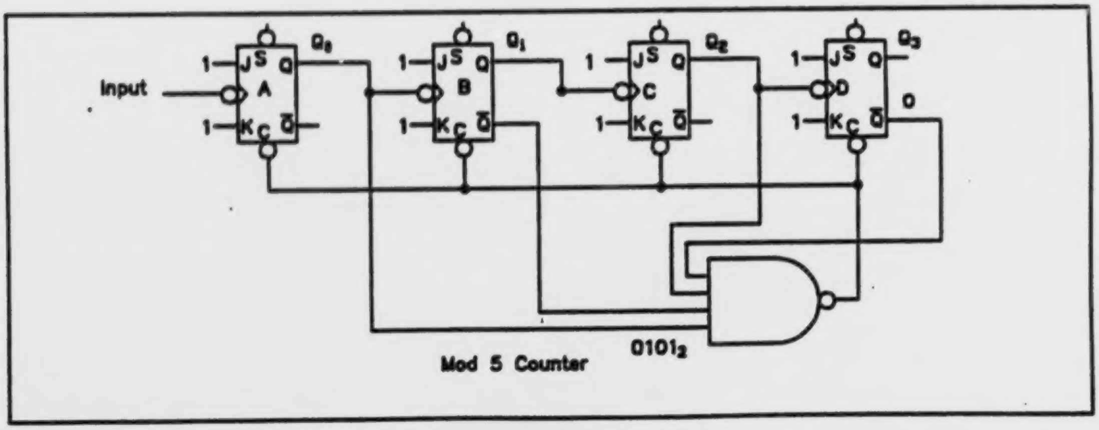
Four Bit Register with Series and Parallel Inputs

Figure 1


Input
Clear Input
1
J
S
Q
K
C
Q̄
A
B
C
D
Q0
Q1
Q2
Q3
Clock
Q0
Q1
Q2
Q3

Four Bit Ripple Counter

Figure 2


Input
1
J
S
Q
K
C
Q̄
A
B
C
D
Q0
Q1
Q2
Q3
0

Mod 5 Counter 0101_2

Figure 3

The third pulse will toggle FF A again to 1, which is the leading edge of the pulse on the Q output. This does not cause FF B to toggle. The fourth pulse will toggle FF A again, giving us the trailing edge on the Q output and toggling FF B to 0. FF B has now toggled so that it has a trailing edge or negative part of the pulse on its Q output, which will toggle FF C to put a 1 on its Q output. This will continue until all the FFs have 1s on their Q outputs.

The next pulse that hits after all the FFs have 1s on their outputs will toggle all the FFs to 0. This will put the counter in position to start counting up again. If we wanted the counter to count down, then we could connect the Q' outputs to the clock inputs. This will cause the ripple counter to count down instead of counting up.

Notice the waveforms for each of the Q outputs below the circuit. Also notice that the waveform for Q_0 will switch on the trailing edge of the clock each time. Then, if you look at the waveform for Q_1, you can see it switching on the trailing edge of Q_0. Notice that the period doubles, or the frequency is halved, for each FF starting with the clock pulse. The frequency on the Q output of FF A is half of the clock frequency, and the frequency on Q_1 is one-fourth the clock frequency, or half of the frequency of Q_0.

This ripple counter is called a MOD 16 ripple counter. The MOD 16 indicates that it will go through 16 different counts. The number 0 through the decimal number 15 is a total of 16 different counts.

MOD NUMBER

The MOD number of a counter is equal to 2^n, where *n* is the number of FFs, if no modifications have been made to the circuit. We can modify the circuit to reduce the MOD number for any ripple counter by making it stop counting and clear at some specific point.

We have modified the ripple counter in figure 3. We have added a NAND gate with its inputs connected to the ripple counter. The NAND gate inputs are set so that when the number 0101 or the decimal number 5 hits the register, the NAND gate will go low and clear the register.

When we include the number 0, this register will count through 5 numbers. After the count of 4, when the next number hits, the register will be cleared by the NAND gate. It never really sees the number 5, since it is cleared instead. The next pulse that it receives after clearing will start it counting again.

This counter in figure 3 is a MOD 5 counter. We can change the number that makes it clear by changing the pick up points that feed the highs into the NAND gate. Notice that we are picking up from the Q or Q' depending on what number we want.

When this register has the number 4 in it, which is a 1 on FF C and 0s on all the other FFs, the next clock pulse will put a 1 on FF A. Remember that we are still looking at the binary numbers backwards on the page. When A goes high, the necessary logic is present to trigger the NAND gate, which clears the register.

The Q_0 output will have to go high to trigger the NAND gate, which clears it and immediately puts the output low. This pulse going up and then immediately going down again results in a spike on that output.

We can make a MOD 10 counter if we changed the inputs to the NAND gate so it would clear the register on the count of 10. This would give us a counter that could be used as a BCD counter.

It would count to 9 and then switch back to 0. If you connected a second MOD 10 counter to the first by making the output from the NAND gate the clock input to the second counter, you would have a BCD counter that could count to 99.

The basic ripple counter does have the limitation of not being able to count fast. The propagation delay accumulates with each additional FF. If each FF has a 30 ns delay, then the total delay for four FFs will be 120 ns. If the period of the input clock pulse is shorter than 120 ns, the counter will not work.

The 74193, which is a TTL parallel three-bit counter, has an added AND gate to allow it to count without rippling. The ripple function of having the output from one FF drive the clock input of the next is eliminated. All the clock inputs are connected, and each FF will switch on the clock input. This chip also has inputs to allow it to be set with a number in parallel, and it can be switched to count either up or down. There are many, more complex, counter chips available for specialized counting applications.

EXERCISE: Read each question carefully, and take your time. Use your notebook paper or scrap paper to solve the problems.

1. What MOD number would a counter with six FFs have?
   A. 32
   B. 64
   C. 68
   D. 16
   E. None of the above

2. What changes would you make in a ripple counter to make it count down instead of up?
   A. Feed the pulses in backwards.
   B. Connect the Q' outputs to the clock inputs.
   C. Reverse the order of the FFs.
   D. Set it to clear on the number 2.
   E. None of the above

3. If each FF in a 5-bit ripple counter had a propagation delay of 108 ns, how long would the propagation delay for the whole circuit be?
   A. 432 ns
   B. 648 ns
   C. 540 ns
   D. 758 ns
   E. None of the above

4. How many clock pulses would you expect the circuit to take to enter the number 10011_2 into a register in parallel?
   A. 1
   B. 3
   C. 6
   D. 9
   E. None of the above

5. What changes would you need to make to use an OR gate instead of a NAND gate to make a MOD 10 counter?
   A. Convert the logic of the OR gate to match the logic of the NAND gate using DeMorgan's theorem.
   B. Pick up the inputs to the OR gate from the inverted outputs of the FFs.
   C. Connect the output of the OR gate to the set inputs of the FFs.
   D. It is not possible to use an OR gate for this purpose.
   E. None of the above

6. What does the small circle and triangle on the clock input to an FF indicate?
   A. The clock input is active during the low portion of the clock pulse.
   B. Triggers on the trailing edge of the clock pulse
   C. Triggers on the leading edge of the clock pulse
   D. The input will only recognize the low portion of the clock input.
   E. None of the above

7. A MOD 8 counter would use how many FFs?
   A. 2
   B. 3
   C. 4
   D. 5
   E. None of the above

8. After 15 clock pulses, what binary number would be on a MOD 10 counter?
   A. 0111_2
   B. 1001_2
   C. 0101_2
   D. 0011_2
   E. None of the above

E-3

Binary Addition

UNIT OBJECTIVE: Upon completion of this instructional unit, the student will be able to demonstrate a knowledge of registers and adders and of circuits that convert analog to digital and transmit data.

SPECIFIC OBJECTIVES: Upon completion of this assignment, the student(s) will be able to demonstrate a knowledge of:

- how a single full adder can add binary numbers
- the full system for adding and subtracting binary numbers

TERMS

Accumulator: The accumulator is one of the registers that is connected to the adder in the arithmetic section of the computer. The accumulator will receive the sum of the numbers added after the add operation.

Adder: The arithmetic unit in the computer that adds binary numbers.

Full adder: The full adder is one unit of an adder. This unit will add two bits and provide a carry-out, as well as a carry-in to receive the carry-out from the previous full adder.

COMPUTER ADDITION

This lesson may be a review of your computer mathematics. If you have not had computer mathematics, your knowledge of algebra will help you understand the following concepts. The computer is simply a collection of switches, and it uses the binary mathematics system to perform its computations. The binary system, as used by computers, has no provision for negative numbers. This lack of negative numbers results in difficulties when the computer needs to subtract two numbers.

In the heart of the computer is the arithmetic unit that adds binary numbers. By using the 2s complement system, the computer can subtract numbers without having to use some code for a negative sign. Although the 2s complement system looks complicated, remember that the system was designed for computers and not people.

The computer has two registers that feed into the adder. If you have the opportunity to program a computer at the assembly language level, you will be dealing with these two registers, which are often labeled A and B. The A register may also be labeled the *accumulator*. The sum of two numbers, when they are added, is sent back to the accumulator where it may be sent on to storage or have another number added to it. The data in these registers can be moved to and from the memory section of the computer. The control section in the computer will provide the signals to operate the adder and move data to and from the memory section.

ADDER

Many students become confused with the addition done by an OR gate and true arithmetic addition. Arithmetic addition is different from the process of combining two bits in an OR gate. An OR gate will combine two 1s and the result is a 1, while the result in arithmetic addition is 10_2.

The two bits we are adding, we can call A and B. If both A and B are 1s, the sum of these two bits is the 0 in our answer and the 1 is carried forward to the next column. This effectively gives us three inputs and two outputs. The three inputs are the A input for one bit, the B input for the other bit, and the carry-in, which may come from another addition process. The truth table below shows these inputs and outputs and their values in an addition process.

A	B	C_{in}	LS	C_{out}
0	0	0	0	0
0	0	1	1	0
0	1	0	1	0
0	1	1	0	1
1	0	0	1	0
1	0	1	0	1
1	1	0	0	1
1	1	1	1	1

Remember that binary mathematics only has 1s and 0s. When you are adding in binary, 1 + 0 = 1 and 1 + 1 = 10. With the carry included, we have 1 + 1 + 1 = 11. Look at the truth table and compare these addition samples. Notice that the position of the input does not change the value in an addition process. The circuit in figure 1 shows a full adder, which is the circuitry that follows the truth table above. This circuit is a full adder; the carry-in is left off on a half adder. You can follow the logic through the circuit and see how it follows the truth table.

If we start with inputs 1 for A, 0 for B, and 1 for the C_{in}, we will have a 0 and 1 on the input to the second XOR gate. The logic output from this gate will be a 1 since the inputs are different. The 1 from this XOR gate and the 1 from the A input will result in a 0 on the sum output.

Remember that an AND gate will need all 1s on its inputs to have a 1 on the output. The A and C_{in} inputs both have a 1 on them, and they both feed into the bottom AND gate in figure 1. As a result, this AND gate will have a 1 on its output, which will be the 1 on the input of the OR gate that results in a 1 on the C_{out} output. If any one of the AND gates has two 1s on its input, it will give a 1 to the OR gate, which will result in a 1 on the carry-out.

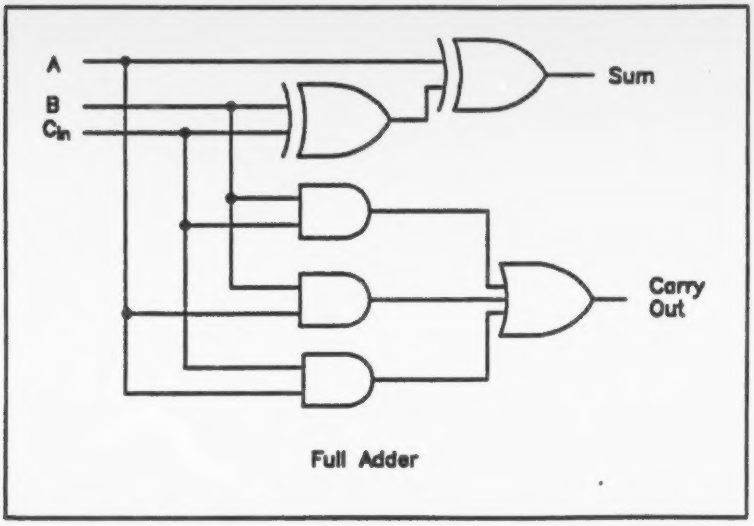

A
B
C_{in}
Sum
Carry Out
Full Adder

Figure 1

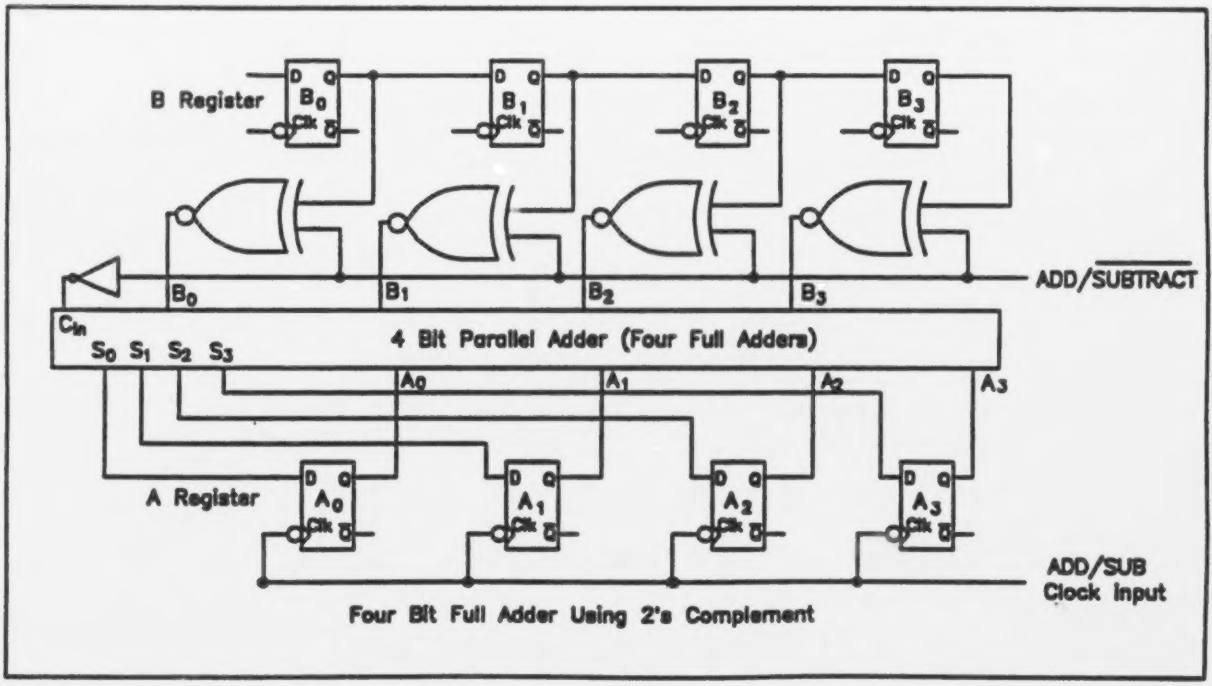

B Register
D Q
B_0
B_1
B_2
B_3
Clk
$\overline{Q}$
ADD/$\overline{\text{SUBTRACT}}$
C_{in}
S_0 S_1 S_2 S_3
4 Bit Parallel Adder (Four Full Adders)
A_0
A_1
A_2
A_3
A Register
ADD/SUB Clock Input
Four Bit Full Adder Using 2's Complement

Figure 2

ARITHMETIC UNIT

These full adders can be combined to add larger binary numbers called *words*. The arithmetic units in home computers will usually have 8-, 16-, or 32- bit word sizes and therefore use 8, 16, or 32 of these full adders in its arithmetic unit. The word size and the number of adders will depend on the design of the microprocessor.

We are using only four full adders in the example in figure 2. The lines and circuitry showing how data could be entered into registers A and B, and how the clock, clear, and set inputs could be used was left out to keep the drawing a little clearer. The drawing of the box in the center is the four full adders with the carry-out of each adder connected to the carry-in of the next adder. The carry-in for the first adder is on the left side of the box. Putting a 1 on the ADD/SUBTRACT line will result in the XNOR gates sending the logic from the B register on to the adder without changing it.

Putting a 0 on the ADD/SUBTRACT line will cause the XNOR gates to invert the logic they receive. This will result in the binary number being inverted before it arrives at the adder circuitry. You have studied the 2s complement system in previous assignments. Remember that the 2s complement system inverted the number and added 1 to it when it received a negative number. Putting a 0 on the ADD/SUBTRACT line changes the number from the B register to a negative number. Also, the 0 on the ADD/SUBTRACT line will be inverted by the inverter before going into the C_{in} input to the first full adder. This provides the 1 that is added to the inverted number for the 2s complement system.

Remember that the 2s complement system creates a negative number by inverting the number and adding 1 to it. The binary number that appears at the four B inputs and the number that appears at the four A inputs will be added. The sum will then appear at the S outputs. These S outputs feed back into the A register and will load or appear on the Q outputs when a clock pulse hits the clock inputs. The circuit operates by accepting the two numbers to be added or subtracted in the A and B registers and loads them to the Q outputs. Once the binary numbers are on the Q outputs, they are also in the adder. The next clock pulse will put the sum from the adder into the A register or accumulator. The data that was in the A register is lost when the new data comes in.

BCD ADDITION

Some circuits have been designed to add binary coded decimals. There is a problem that a BCD adder has to be designed to handle. The binary numbers for digits over 9 in the decimal system do not exist in the BCD system. The BCD system uses four bits for the numbers 0 through 9. Four bits will also give a decimal number up to 15 in straight binary. The numbers 10 through 15 are not valid BCD numbers. During the adding process, numbers that are not valid BCD numbers will be generated.

If we take the number 15 and subtract the maximum BCD number of 9 from it, we get 6. Now when the BCD adder system sees an illegal BCD number, it adds 6 to it and carries 1. Additional circuitry is added to the BCD adder to accomplish this. By adding 6 and carrying the 1, we will have taken the illegal number and converted it back to a legal BCD number.

Let's try an example by adding the decimal numbers 6 and 8. This gives 14, which is, of course, not a valid 4-bit BCD number.

```
 6   =  0110
+8   =  1000
--      ----
14      1110      (1110 is not a valid BCD number)
+6      0110
        ----
0001    0100
```

Notice, in the example, that when we add the 6 and the 8 in binary, we get a binary 14. Next we added the 6, and we had a 1 which carried out of the 4-bit word that was available. This 1 was moved to the next higher 4-bit BCD word. The result is two words; the one on the left gives us the 1 for the 14, and the word on the right gives us the 4 for the 14. Now we have a valid BCD number.

CARRY PROPAGATION

The circuitry shown in figure 2 will have a problem with propagation delay. The delay from each adder as the carry moves through the complete adder can cause problems. The clock speed would have to run slowly so the carry would not get behind any additional adding that the circuit would be doing.

This problem has been solved with additional circuitry. This needed circuitry is designed to speed up the process of addition by eliminating the propagation delay that comes from a carry being carried through all of the adders. If we had a 32-bit adder, which is common in many home computers, and there were a 60 ns propagation delay between the input of a carry and the output that resulted from it, the total propagation delay for the 32-bit adder would be 32 times 60 ns, or 1.9 μs.

This 1.9 μs of delay is unacceptable for a fast computer. The circuitry that has been designed to solve this problem is called the *look-ahead carry*. Additional logic gates are used to examine the inputs and determine if a carry is going to be generated. A large amount of extra circuitry is needed to accomplish this, but it can all be put in one integrated circuit. Thus, the additional circuitry is easily justified.

MULTIPLICATION AND DIVISION

By simply providing the correct instructions to the adder, the basic adder circuitry can be used for multiplication and division. Multiplication is addition performed a large number of times, and division is subtraction performed a large number of times.

When you multiply, using pencil and paper, you shift the columns of numbers and add the totals. You multiply in binary using the same method. Multiplying in binary is easy since there are only 1s and 0s to work with. It is either 1 times the number or 0 times the number, which results in zero or the number itself.

When we have a 1 times the number, then it is only necessary to shift the number depending on which column we are working in and add the numbers. The adder circuitry can only add two numbers at a time. The high speed in which the adder is able to perform these calculations eliminates the problem of the extra steps the computer will be taking.

Division is done in the same manner. Remember that when you do division longhand, you subtract the numbers and shift the numbers in a manner similar to multiplication. Making the adder do this division or multiplication is mostly an exercise in programming. Writing a program to make an adder multiply or divide requires a clear understanding of how multiplication and division work.

EXERCISE: Read each question carefully, and take your time. Use your notebook paper or scrap paper to solve the problems.

1. What should the inputs be to get a 1 on both the sum and carry-out of a single full adder?
   A. 1 on A, 0 on B, and 0 on C_{in}
   B. 0 on A, 1 on B, and 1 on C_{in}
   C. 1 on A, 1 on B, and 1 on C_{in}
   D. 1 on A, 1 on B, and 0 on C_{in}
   E. None of the above

2. The 7483 adder chip has four adders in it. How many 7483 chips would it take to build a 64-bit adder?
   A. 64
   B. 32
   C. 16
   D. 8
   E. None of the above

3. If it takes a carry 65 ns to pass through one adder, how long would it take for a carry to ripple through a 64-bit adder?
   A. 41.6 µs
   B. 10.4 µs
   C. 1.04 µs
   D. 4.16 µs
   E. None of the above

4. What function is missing in OR gate addition that arithmetic addition has?
   A. The OR gate does not have enough outputs.
   B. The OR gate cannot do 2s complement.
   C. The OR gate has no carry function.

D. The OR gate cannot handle large numbers.
E. None of the above

5. What is the register called that receives the sum after addition in a full adder circuit?
A. Accumulator
B. B register
C. Parallel adder
D. XNOR
E. None of the above

6. How does the computer know when a binary number, in a 32 bit adder, is negative when the number is in the accumulator?
A. The number is not a valid ordinary binary number.
B. The MSB will be a 1.
C. It remembers the status of the number.
D. Negative numbers are all below zero.
E. None of the above

7. Why do we need to carry 1 into the adder for the subtraction process?
A. Because the process loses a bit
B. To identify a subtraction process instead of division
C. To fill the empty spaces in the register holding the final results
D. The 2s complement system requires it.
E. None of the above

8. What problem would there be if the total carry propagation delay in a 64-bit adder were 5 µs and the clock input to the accumulator would hit 4 µs after the numbers were received by the adder?
A. The adder would wait for the carry to complete before going on with the addition.
B. The carry process would jump ahead when the clock input arrived to save the number.
C. The addition process would fail, and the result would be garbage.
D. The adder would only respond to every other clock input.
E. None of the above

E-4

Decoders

UNIT OBJECTIVE: Upon completion of this instructional unit, the student will be able to demonstrate a knowledge of registers and adders and of circuits that convert analog to digital and transmit data.

SPECIFIC OBJECTIVES: Upon completion of this assignment, the student(s) will be able to demonstrate a knowledge of:

- how a decoder works
- LED and LCD display systems

TERMS

Decoder: The decoder will take a binary number and activate one or more of its outputs based on the binary number of the input.

LCD: Liquid crystal display, a common method for displaying numbers. Most digital watches and calculators use this display.

Seven-segment display: An arrangement of seven segments that can be made visible. When the proper segments are made visible, the display will show any decimal number and some letters.

ENCODERS AND DECODERS

Some digital ICs functions as encoders and some as decoders. The decoder will accept a binary number on its input, and one or more of its output lines will then go active depending on the binary number that was present on its input. The encoder will turn this around, and its output is a binary number that is based on activating one of its inputs.

If you remember what you learned from your algebra class and look at the decoder mathematically, you can say that the decoder with N number of inputs will have the capability of 2^N number of outputs. For example, a decoder with three inputs will have the capability of 2^3, or 8, outputs.

A BCD input, which is four inputs, would allow 16 outputs. The BCD logic, however, only handles decimal numbers to the number 9, which is 10 outputs not 16. Many of the BCD to 10 output devices will not have an output if they are activated by a binary number that is not a valid BCD number.

If the inputs and outputs on an encoder or decoder are active low, they will have small circles or bubbles on them. An active high input or output will be plain. The abbreviation for the term input and output is *I/O*.

BCD TO DECIMAL DECODER

A decoder chip that changes BCD to decimal is the 7442. This chip has a BCD or 4-bit input and 10 outputs. The schematic symbol of the 7442 will show bubbles on all the outputs. This means the outputs of this device are active low. The inputs to the 7442 are all active high.

The outputs will all stay high, which means no output, if the input is not a valid BCD number. The 7442 has the totem pole outputs while its sister chip, the 7445, has the open collector outputs. There is no difference in the logic between the 7445 and 7442. Only the outputs are different.

BCD TO SEVEN-SEGMENT DRIVER

The 7447 and the 7448 are another pair of chips that are basically the same chip with different outputs. These chips are BCD to seven-segment decoders. They will take a BCD number and change that logic to the logic that is necessary to light up the seven segments for the decimal number represented by the BCD number.

The 7448 is an active high device and the 7447 is active low. These particular devices will have more than one output going active depending on the input. They are designed to drive the seven-segment numbers that you are familiar with on calculators and digital watches. The number of outputs that go active will depend on the number that is being displayed.

LED displays are not as common now as they once were, but there are still many of them around. The LED (light-emitting diode) requires more current than the LCD (liquid crystal display). The 7447 and 7448 are only suitable for the LED displays, and not the LCD displays.

The seven-segment LED display will have either the anode or cathode of each of the light-emitting diode segments in the display all connected and brought out of the display on a common pin. A common anode display will have all the anode ends of the segment diodes connected to one output pin on the display.

The active low device, or 7447, would be used to drive the common anode display. The 7448 would be used to drive the common cathode display. Some of the features of this device can only be appreciated when you look at what it is designed to do. A lamp test input, for example, will turn on all of the segments to test the seven-segment display for any segments that may have failed. Also, a ripple blanking input and output will keep the display from showing numbers that are not correct. If the circuit that this display is connected to has an output while it is computing, like a ripple counter, the display can be turned off until the ripple counter has become stable.

LIGHT-EMITTING DIODE DISPLAY

The seven-segment display is a basic type of display. It is primarily useful for displaying numbers. The seven-segment is used with the LED display, LCD display, and other types of displays that can give a short segment which can be turned on and off.

The LED was one of the most common seven-segment displays. In many applications today it has been replaced by the LCD. Each segment of the LED display will have one or two LED diodes in it and will require from 5 to 30 mA of current. In addition to the high current requirements, LED displays are often difficult to see in bright sunshine. The LED display is constructed to have all of the segment diodes connected at one end. This end is then brought out and labeled as a common pin. This common pin can be either a common anode or a common cathode, depending on which end of the diode is connected to the common line. If you attempt to use a common anode where a common cathode is required, the diodes in the device will be backwards and will not light.

Figure 1 shows the pin connections for each of the segments, which are labeled from A to F. This labeling is standard in the industry for LED seven-segment displays.

Remember that LEDs must have resistance in series with the diode. The resistance is used to limit the current through the diodes. A current-limiting resistor is needed for each of the segments in the seven-segment display.

Desk calculators and other equipment often require a number display with many numbers or many different seven-segment displays. Each of the displays will have 8 or 9 pins, and if a decimal point is added or a minus and plus sign, there will be additional pins. A display with 10 numbers would result in 10 times the number of pins for each display.

When a display has a lot of numbers, additional circuitry is used to avoid separate lines for each of the pins on all of the displays. All of the individual pins that pick up the different segments are in parallel. The entire display is multiplexed so that only one number is turned on at a time, although all the displays are in parallel. The common line is switched so that the numbers are turned on in sequence over and over again at a rate that looks like they are all lighted together, when only one number is on at any one time.

To understand how this works, we can look at the number 2 pin. All of the number 2 pins, which connect to the segment F, are connected in common with the driver. As each number's turn comes up to be turned on, power would be applied through the common line to the display. Only the one display unit would receive power. If all of the units were to receive power, then all units would display the same number. All of the display units would see their segments activated, but only one of the display units would light up because only one would have power coming into it from its common pin.

The amount of current that is pulsed through each of the display units will be higher since they are on for only a short time. To get the same brightness, it is necessary to increase the current. This does not create a problem with the display because the diode does not have a chance to heat up and burn out during the short time it is on. The average amount of current that is fed through the display will be within the specified amount for steady current.

LIQUID CRYSTAL DISPLAYS

The LCD and its variations have become the most popular type of display for calculators and other portable displays. The LCD can use the same seven-segment display system used with the LEDs. Also, a variety of dot matrix systems are used with LCD systems to display letters and numbers. Color has even been added to LCD systems.

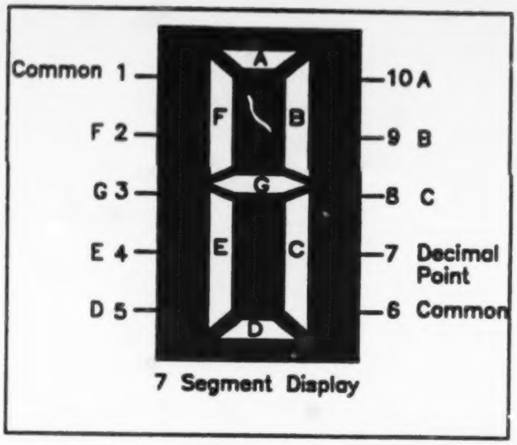

Common 1
F 2
G 3
E 4
D 5
10 A
9 B
8 C
7 Decimal Point
6 Common
A
B
C
D
E
F
G
7 Segment Display

Figure 1

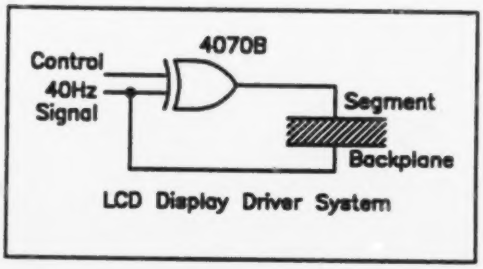

4070B
Control
40Hz Signal
Segment
Backplane
LCD Display Driver System

Figure 2

The LCD has a major advantage over the LED in the amount of current it needs. The LCD needs very little current, and it can be seen in bright sunlight. Unlike the LED, the LCD does not generate any light of its own. The LCD only *reflects* light. To get an LCD segment to reflect light, a low frequency ac signal is placed across the segments. This causes them to change their crystalline structure. The change in crystalline structure causes the segment to reflect light instead of allowing it to pass on through.

The backplane of the LCD, which covers the whole back of the display, acts like part of a capacitor. The segments are like the other plate of that capacitor. The low frequency of the ac signal across this capacitor results in a high capacitive reactance and low current flow.

Figure 2 shows an XOR gate feeding the segment with a 40 Hz signal. Remember the logic of an XOR gate; when the inputs are the same, the output will go low, and when the inputs are different, the output goes high. When the control input to the XOR gate is low, the 40 Hz signal will not be changed coming out of the gate. This results in equal voltages across the segment and backplane. As a result of the equal voltages, the segment will remain clear. When the control input goes high, the XOR gate inverts the signal output. This will result in ac across the LCD. The ac will cause the segment to become opaque and appear black.

The frequency of the signal that is fed across the LCD is low enough to avoid a low capacitive reactance and high enough to avoid any flickering. A higher capacitive reactance will result in lower current consumption.

EXERCISE: Read each question carefully, and take your time. Use your notebook paper or scrap paper to solve the problems.

1. List the binary numbers that, if present on the inputs of a BCD to a seven-segment decoder, would activate the segment E.
   A. 1000_2, 0101_2, 0001_2, 0100_2
   B. 0001_2, 0000_2, 1100_2, 1110_2
   C. 0000_2, 0010^2, 0110_2, 1000_2
   E. None of the above

2. What would you use the ripple blanking input for?
   A. To reduce any ripple noise on the display
   B. To cause the blanking to turn on and off
   C. To feed a ripple signal into
   D. To momentarily turn off the display to avoid figures and numbers that should not be displayed
   E. None of the above

3. What is the maximum number of outputs that a decoder with six inputs can have?
   - A. 12
   - B. 32
   - C. 64
   - D. 36
   - E. None of the above

4. What is the difference between a common anode and a common cathode LED display?
   - A. One gives off a red light and the other a green light.
   - B. The polarity of the display changes.
   - C. One is brighter than the other.
   - D. The common anode is more common than the common cathode.
   - E. None of the above

5. How many inputs and outputs does a decoder have that will accept up to 32 different binary combinations on its input?
   - A. 4 inputs and up to 36 outputs
   - B. 6 inputs and up to 32 outputs
   - C. 5 inputs and up to 32 outputs
   - D. 8 inputs and up to 28 outputs
   - E. None of the above

6. What output will the 7442 have if the input is 1010?
   - A. a, b, c, d, e, and f
   - B. b and c only
   - C. a, b, g, c, and d
   - D. a, b, c, d, e, f, and g
   - E. None of the above

7. What difference is there between an LCD and an LED display?
   - A. One handles numbers and the other letters.
   - B. The LED is faster than the LCD.
   - C. The LED runs at a higher frequency than the LCD.
   - D. The LED makes its own light, and the LCD reflects light.
   - E. None of the above

E-5

Encoders and Multiplexers

UNIT OBJECTIVE: Upon completion of this instructional unit, the student will be able to demonstrate a knowledge of registers and adders and of circuits that convert analog to digital and transmit data.

SPECIFIC OBJECTIVES: Upon completion of this assignment, the student(s) will be able to demonstrate a knowledge of:

- how an encoder works
- how a multiplexer works
- how a demultiplexer works

TERMS

Encoder: The encoder is a circuit usually built into an integrated circuit that will accept one input. This one input will be used to activate a binary number on the output.

Multiplexer: This circuit will take many inputs and direct one of the inputs to an output. The demultiplexer is the reverse of this, taking one input and directing it to one of many outputs.

ENCODER CIRCUITRY

The decoder circuit is designed to receive a binary number on its input and use this binary number to activate one of its outputs. ***The mathematics courses you have taken will help you understand these new circuits.*** The encoder is the opposite of the decoder. The encoder will receive an input on one of its input lines, and that input will result in a binary code on the output.

The 74147 IC, which is a decimal to BCD encoder, has nine inputs and four outputs. There is no input for 0 because the logic does not require it. A 0 input is no input, and no input will leave all outputs inactive or at 0. If the number 4 input is activated by going low, the output will be the binary number for 4. This chip has an added feature called *priority decoding*. Priority decoding means it will accept the highest input that is activated and ignore the rest. If the inputs 4, 6, and 8 are all low or activated, the output will be the binary number for 8. The circuit will ignore the inputs 4 and 6 which are below line 8.

The 74148 encoder has eight input lines and three output lines. This encoder has the added feature of an enable input line and an enable output. These enable lines allow this chip to be cascaded to form a much larger circuit.

MULTIPLEXER

The multiplexer circuits take the encoder circuitry a little further. The 74151 chip is a typical example. This multiplexer has eight inputs and one inverted output. It has a three-bit select input that will select one of the inputs and allow the signal on that input to pass on through to the output.

If the binary number for 4 is on the three-bit select input, this number 4 will select the fourth input to the chip. Whatever is on this number 4 input will pass on to the output. This feature can be very useful for switching a group of signals, one at a time, by using binary numbers for the signal to be switched.

A computer can be set up to monitor a group of systems. It will do this by sampling each one in turn. The 74151 chip can be used for this sampling. The 74151 chip is also useful for making a logic circuit. The chip can be programmed for any logic requiring the same number of inputs as provided by the 74151's select inputs.

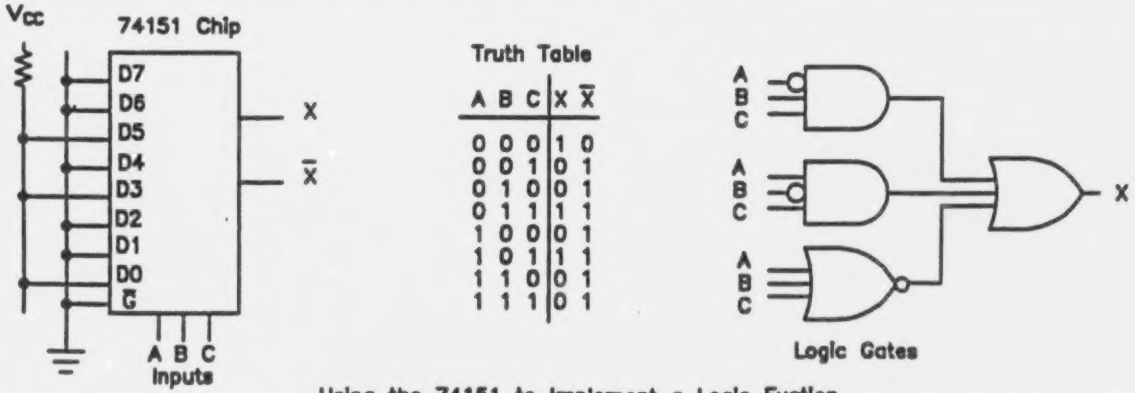
Figure 1 shows a 74151 chip, the truth table, and a logic diagram. The truth table is for the logic gate circuit next to it. As you can see, this logic circuit consists of two AND gates, each with one inverted input and one NOR gate and OR gate. Since an integrated circuit usually only has one type of gate in it, it would take three integrated circuits to build this logic circuit.

The 74151 chip, next to the truth table, has been wired to give the same logic as the logic diagram on the right in figure 1. If the logic input that is put on the A, B, and C inputs to the logic diagram is put instead on the three select inputs of the 74151, the output will be the same on both circuits.

Let's use, as an example, three 0s or 000_2 on the inputs. If we start at the top of the truth table with the three 0s, which should put a 1 on the X output, and look at the 74151, you will notice that the binary number 000_2 will activate D0 which is connected to a high or 1. This will pass on through to the output and give us a 1 on the output. The next line down in the truth table is the 001_2 or number 1 in binary. The truth table shows a 0 for this on the output. The 74151 shows the number 1 input to be tied to ground, which will give a 0 on the output.

The 74151 can be wired for any logic that does not exceed its number of inputs. This circuit will allow us to quickly put together any logic circuit.

The 74151 can be used to convert parallel data to series for transmitting to another location. To transmit data in parallel requires one line for each bit. Transmitting in series will require only one line although the process is slower. To use the 74151 for converting parallel to series, the data is entered into the eight inputs. A 3-bit counter like a MOD 8 ripple counter can be used to feed into the select inputs. The select inputs will cycle through the eight inputs. The result of using the 74151 chip for this conversion will be taking each of the eight inputs one at a time and feeding it to the output. The parallel data present on the eight inputs will be converted to serial data coming out the output of the 74151.


Vcc
74151 Chip
D7
D6
D5
D4
D3
D2
D1
D0
G̅
X
X̅
A B C
Inputs
Truth Table
A
B
C
A
B
C
A
B
C
X
Logic Gates

A	B	C	X	$\overline{X}$
0	0	0	1	0
0	0	1	0	1
0	1	0	0	1
0	1	1	1	1
1	0	0	0	1
1	0	1	1	1
1	1	0	0	1
1	1	1	0	1

Using the 74151 to Implement a Logic Fuction

Figure 1

DEMULTIPLEXER

The opposite of the multiplexer circuit is the demultiplexer. The demultiplexer will take the input from one input line and send that input to the output designated by the select control inputs. Decoders and multiplexer circuits can be the same circuit.

The decoder chip which you studied earlier can be used as a multiplexer by adding an enable input. This enable input will turn off all of the outputs when it is not active. When the enable input is active, it will allow the selected output to go active. When the enable input is used as the data input, the logic of the circuit is the same as a multiplexer. The 74138 is one of these chips. It is called a *decoder/multiplexer* by the manufacturer.

The 74138 has one input and eight outputs, and the 74139 has two multiplexers in one chip. Each of the two multiplexers is a one-input and four-output device with two select inputs for each multiplexer. This device has an active low output just like the 74138.

The 74137 is another chip with an interesting feature. This chip is similar to the 74138 with the three select inputs, one enable input, and eight outputs. The enable input is used as the data input when it is used as a multiplexer.

The 74137's added feature consists of the flip-flops on the select inputs. These flip-flops can be used to store the input data. They are enabled by an input called the *latch enable*. When the latch enable is low, the flip-flops will have no effect on the circuit. With a low on the latch enable, the circuit will behave just like the 74138. When the latch enable goes from a low to a high, which is the leading edge of a pulse, the data that is currently present on the select inputs during the transition will latch into the flip-flops.

The data is stored in the flip-flops and will remain there as long as the latch enable remains high. Any further changes in the logic applied to the select inputs is ignored while the latch enable is high. The data in the flip-flops selects the output during this time. Until the latch enable goes low and is ready to accept changes in its input, the data stored in the flip-flops will continue to control the output.

This chip is designed to work in a large system that may have noise pulses that can give false readings to the select enable. The latch enable input allows the design of a circuit that will only accept an input on the select inputs when the latch enable pulses low momentarily.

EXERCISE: Read each question carefully, and take your time. Use your notebook paper or scrap paper to solve the problems.

1. Which circuit would you use—a multiplexer, encoder, decoder, or demultiplexer—for a computer to read the status of six remote stations one at a time in sequence?
   A. Encoder
   B. Multiplexer
   C. Decoder
   D. Demultiplexer
   E. None of the above

2. If the four inputs, 5, 3, 2, and 8, on a priority encoder are active, what binary number would be on the output?
   A. 5
   B. 3
   C. 2
   D. 8
   E. None of the above

3. What is the 74147 IC?
   A. Decoder
   B. Multiplexer
   C. Encoder
   D. Demultiplexer
   E. None of the above

4. You have a logic circuit that consists of an XOR gate feeding one input of an XNOR gate, which gives you three inputs and one output. Select the list of correct inputs to the 74151 starting with D0 to make this circuit.
   A. 0, 0, 1, 1, 0, 1, 1, 0
   B. 1, 1, 0, 1, 0, 1, 1, 0
   C. 1, 0, 0, 1, 0, 1, 1, 0
   D. 1, 0, 0, 1, 0, 0, 1, 0
   E. None of the above

5. What does the latch enable on a 74137 do?
   A. It releases the input data to allow it to go to the output.
   B. It allows the output to latch on.
   C. It turns on the chip.
   D. It enters the data into the flip-flops.
   E. None of the above

6. To use a decoder as a multiplexer, what additional input is required?
   A. Latch enable
   B. Enable input
   C. Select input
   D. Extra data input
   E. None of the above

7. What is the 74138 IC?
   A. Decoder/multiplexer
   B. Seven-segment driver
   C. Encoder
   D. Demultiplexer
   E. None of the above

E-6

One Shot and Schmitt Triggers

UNIT OBJECTIVE: Upon completion of this instructional unit, the student will be able to demonstrate a knowledge of registers and adders and of circuits that convert analog to digital and transmit data.

SPECIFIC OBJECTIVES: Upon completion of this assignment, the student(s) will be able to demonstrate a knowledge of:

- how a Schmitt trigger works
- how a one shot works
- the CMOS transmission gate

TERMS

Schmitt trigger: This circuit is used to speed up the rise and fall times of a slow pulse. It also will clean up noisy pulses by switching on at a different voltage than the voltage that will switch it off.

One shot: This circuit will put out a pulse with a controlled width. The width of the pulse depends on an external capacitor and resistor that can be added to the circuit.

Decoupling: Adding small value capacitors to a TTL digital circuit to filter the power supply.

CURRENT TRANSIENTS

It is important that digital circuits be free of current transients, or *spikes*. The totem pole output on many of the TTL digital circuits will create a momentary spike. When the output of a totem pole circuit is switching from low to high, the two output transistors will momentarily both be conducting. They only conduct for a short period of time, usually less then 3 ns.

The reason they are both on for this brief time involves the saturation of the bottom transistor in the totem pole. When a transistor is conducting heavily or in saturation, it will take longer to switch to the off state. The transistor on top of the totem pole will switch faster than the bottom transistor because it is not conducting and does not have a problem with saturation. As much as 50 mA of current can be drawn when the two transistors are both in the on condition.

Other factors will also create spikes in a digital circuit. These spikes can appear as pulses to some digital circuits or suppress a valid pulse resulting in a failure of the circuit.

Your algebra background will help you work the formula in this assignment. To solve the problem of spikes and current transients in digital circuits, capacitors are added to filter the power supply. A large capacitor, often an electrolytic around 20 µF, should be added where the V_{CC} first enters the printed circuit board, and small RF capacitors, such as 0.01 µF disk ceramics, should be added very close to the V_{CC} inputs on each of the digital chips on the board. These capacitors should be bridged from V_{CC} to ground with short lengths of wire if any wire is used. This solution to the spike problem is called power supply decoupling.

SCHMITT TRIGGER

The signals that drive TTL circuits must switch relatively fast. A rise or fall time of more than 50 ns can cause erratic triggering of flip-flops and oscillations from logic gates. The pulse should not take any longer than 50 ns to go from a low to a high or high to a low.

A Schmitt trigger input, to a digital circuit, can be used to compensate for a slow rise and fall time of a digital pulse. The Schmitt trigger circuit uses positive feedback to trigger on different voltages of the rise and fall of the input pulse. This variation in triggering is called *hysteresis*.

Designers usually put Schmitt trigger circuitry in the input of their circuits. This Schmitt trigger symbol in figure 1 indicates that this inverter has a Schmitt trigger input. The 7414 is an inverter with the Schmitt trigger circuitry in the input. The square symbol, inside the inverter symbol, with the extended lines on top and bottom is the symbol for the Schmitt trigger.

The 7414, made by Texas Instruments, will trigger its output high at an input voltage slightly over 1.6 V and trigger its output low when the voltage falls to about 0.8 V. The 7414 has a rise time of 15 ns and a fall time of 6 ns on its output.

ONE SHOT

The one shot (OS) is used when an output pulse of a specific pulse width is needed. The one shot or monostable multivibrator will usually have a Schmitt trigger in its input circuitry. This circuit is similar to the flip-flop with two outputs. The two outputs are the inverse of each other.

The OS has only one stable output. When it receives a triggering pulse, it will switch to its new state and remain there for a timed period and then return to its original state. The new state can be the high of a particular pulse. The amount of time that the OS will remain in its triggered state is determined by a resistor capacitor combination or the RC time constant.

The 74121 has a 2 kΩ resistor built into the device and can operate with or without an external capacitor. Increasing the capacitance or adding additional resistance will increase the RC time constant and the pulse width.

The 74121 can put out a pulse width from 30 ns to 28 seconds. With no external capacitance or resistance, the 74121 will put out a pulse width of from 30 to 35 ns. The following formula can be used to determine the pulse width from the OS.

$T_W = 0.7CR$ *formula 1*

This formula tells us that we can multiply the capacitance times the resistance times 0.7 to get the pulse width in seconds. If we added a 0.01 µF capacitor and 4 kΩ of resistance to the OS, it would give us a pulse width of 28 µs.

The 74121 is a nonretriggerable OS. This means that once the circuit has been triggered, it will go through its complete cycle before it can be triggered again. The 74122, which is similar to the 74121, is a retriggerable one shot. This means it can be triggered again during a pulse. When the 74122 is triggered during a pulse, the timing starts over on the pulse. We could continually keep the output active by triggering it before the output pulse was gone. If the trigger input arrives faster than the output pulse width, the output will remain active.

There is a clear input on the 74122 that can be used to stop a timed pulse. A common application for one shots is in frequency counters. They are used to provide a timed pulse to clear the counter and the display between samples of the input frequency.

CMOS TRANSMISSION GATE

Another interesting device, which is not similar to any other digital or linear device, is the transmission gate. This device uses JFET and CMOS technology. CMOS stands for complementary metal oxide semiconductor, and JFET stands for junction field effect transistor. You have studied the MOS and JFET devices in a previous assignment.

The transmission gate is a switch that can be used to control both digital and analog signals. The bilateral switch has both a P channel and an N channel FET device to get both polarities in the device. The control signal will be applied directly to the N channel and through an inverter to the P channel to turn both sides on at the same time. The resistance of the device when it is on is approximately 200 Ω, which is typical for FET devices. The resistance when it is off is thousands of megohms.

The 4016 integrated circuit, which is a CMOS device, has four switches in one package with individual controls on each switch. The input signal that is allowed must not exceed the voltage of the power source or V_{DD} that is supplying the switches. An improvement over the CMOS design uses JFETs. JFETs are not as delicate and subject to failure from static charges as the CMOS. They also have less input capacitance

The MUX-08 is an eight-channel multiplexer that connects a single input channel to one of eight outputs based on the three-bit select input. The special handling that is required for MOS devices to avoid static charges blowing the input gate is not required with the JFET device.

The MUX-24 has two groups of four switches in the one chip which can be used to feed an op-amp. This type of circuitry can be helpful to eliminate common mode signals.

Because these devices can be switched on very fast and have all of the advantages of being solid state, they are often used where a sound source must be switched on quickly.

EXERCISE: Read each question carefully, and take your time. Use your notebook paper or scrap paper to solve the problems.

1. What voltages will the 7414 inverter with the Schmitt trigger input trigger on?
   A. 2.3 V and 1.2 V
   B. 1.8 V and 0.4 V
   C. 1.3 V and 0.6 V
   D. 1.6 V and 0.8 V
   E. None of the above

2. What is the slowest rise time that is acceptable for TTL circuits?
   A. 100 ns
   B. 50 ns
   C. 50 ms
   D. 250 µs
   E. None of the above

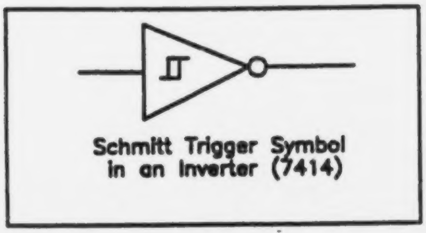
3. Calculate the pulse width from a one shot with 0.1 µF capacitor and 4 kΩ resistor as the external timing components?
   A. 120 µs
   B. 180 µs
   C. 280 µs
   D. 340 µs
   E. None of the above

4. If a transmission gate is in a circuit with 9 V V_{DD}, and the signal being switched is a sine wave, what is the maximum voltage of the sine wave that can be switched?
   A. 4.5 V
   B. 9 V
   C. 12 V
   D. 18 V
   E. None of the above

5. What is the full range of pulse widths that the 74121 can put out?
   A. 45 ns to 230 ms
   B. 120 ns to 1.5 minutes
   C. 30 µs to 28 ms
   D. 30 ns to 28 seconds
   E. None of the above

6. Approximately how much resistance does a transmission gate have when it is on?
   A. 400 Ω
   B. 300 Ω
   C. 200 Ω
   D. 100 Ω
   E. None of the above

7. What is the primary difference between the 74121 and the 74122?
   - A. The 74121 is nonretriggerable; the 74122 can be retriggered.
   - B. The 74121 has lower current requirements.
   - C. The 74122 is CMOS, and the 74121 is TTL.
   - D. The 74121 can put out larger pulses than the 74122.
   - E. None of the above



Schmitt Trigger Symbol in an Inverter (7414)

Figure 1

E-7

Interface with the Linear World

UNIT OBJECTIVE: Upon completion of this instructional unit, the student will be able to demonstrate a knowledge of registers and adders and of circuits that convert analog to digital and transmit data.

SPECIFIC OBJECTIVES: Upon completion of this assignment, the student(s) will be able to demonstrate a knowledge of:

- how a digital analog convertor works
- how an analog digital convertor works
- the flash analog digital convertor

TERMS

ADC: The analog digital convertor, or A/D convertor, will have a digital or binary number on its output that is based on an analog input.

DAC: The digital analog convertor, or D/A convertor, will have an analog output that is based on the digital number in its input.

CONVERTING BETWEEN ANALOG AND DIGITAL

We live in a world that can be described as analog in nature. The computer is digital in nature. Computers are used to monitor and control various processes in the world of an analog nature. This assignment will cover the circuits used by the computer to control and receive information from the analog world.

The circuitry required to interface between the digital computer world and the analog world is called DAC and ADC. DAC stands for digital analog convertor, and ADC stands for analog digital convertor. These circuits will convert from the 0 and 5 V logic levels used by the computer to the variable voltage levels used in the analog instruments and by the analog control devices. ***Your background in algebra should help you to look at these devices mathematically.***

DAC CIRCUITRY

The input to a DAC (digital analog convertor) circuit is a digital code or binary number. This binary number is usually called a binary word. The binary word is fed into the DAC's input in parallel. Another abbreviation for DAC is D/A convertor. The analog voltage, which is the output from the D/A convertor, will have a value that is proportional to the value of the binary word that was on the input of the DAC.

A 4-bit binary word on the input of a DAC will give 16 changes into the input. This means that the 4-bit code can result in 16 variations of analog voltage on the output. If the voltage ranges from 0 to 15 V on the output of the D/A, then each increase of 1 bit in the digital number on the input will increase the voltage on the output by 1 V.

Remember from your previous studies that the total number of changes, or the total number of different numbers, is equal to 2^n. The letter *n* equals the number of bits in the number. The total number of steps in the output of a DAC circuit will be $2^n - 1$, or 1 less than the number of different changes.

For our example, this means the resolution per step is 1 V. Each step is the change of 1 bit. The resolution is often expressed as a percentage of the total voltage. One volt divided by 15 times 100 gives 6.67% resolution for our example.

Another way to find the percentage resolution is to use the formula which has as its input the number of steps. The number of steps will be 1 less than the total number of changes. The percentage resolution is equal to $1/(2^n-1)$ times 100.

$$\text{Percentage resolution} = \frac{1}{2^n-1} \times 100$$

The resolution is important. To understand resolution, think of an analog voltage smoothly increasing and visualize a graph of this. The voltage from our DAC will be in steps and not completely smooth. The better the resolution, the closer we will come to this smooth increase.

The formula for the percentage resolution tells us that the resolution of a DAC is based on the number of steps. The number of steps is also the bit size of the input. The resolution is not a function of the voltage levels on the output.

Several methods are used to make a D/A circuit. The simplified method shown in figure 1 will help you understand the theory behind converting digital signals into analog voltages. Designers have devised many different methods of converting digital to analog. The exact circuitry is not as important as understanding what the chip can do.

There is additional circuitry in figure 1 that is not shown. For this circuit to work properly, the inputs must have accurate voltages. In this example, we will assume that the voltages are all accurate, which is not normally the case with digital circuits. The inputs I_0, I_1, I_2, and I_3 are the 4-bit parallel input.

Remember your studies of op-amp amplifier theory. You learned that the formula for the gain of an inverting amplifier circuit was equal to the feedback resistor R_F divided by the series resistance in the input circuitry of the op-amp. The gain for a signal coming in the I_3 input will be 1,000 divided by 1,000, or unity gain. Since this is an inverting amplifier, the output voltages will be negative with positive voltages on the input.

The second input will have a gain of 0.5, the next input will have a gain of 0.25, and the LSB input will have a gain of 0.125. If we started with all 0s on the inputs or 0 V on all inputs, then the output will be 0 V as well.

A 1 on the LSB position, or 5 V on this input, will give us 0.625 V on the output. This is the resolution of our D/A convertor. Going to the number 2 puts 5 V on input I_1 and 0 V on the other inputs. The gain of 0.25 times 5 gives us an output of 1.25 V.

The output we had with the binary 1 on the input was 0.625. Doubling this gives the same output as putting the binary 2 or 10_2 on the input. The output voltage will be a function of the input voltages The voltages and their logic levels are listed here.

Logic Input	Output Voltage	Decimal Equivalent	Logic Input	Output Voltage	Decimal Equivalent
0000	0 V	0	1000	-5.000 V	8
0001	-0.625 V	1	1001	-5.625 V	9
0010	-1.250 V	2	1010	-6.250 V	10
0011	-1.875 V	3	1011	-6.875 V	11
0100	-2.500 V	4	1100	-7.500 V	12
0101	-3.125 V	5	1101	-8.125 V	13
0110	-3.750 V	6	1110	-8.750 V	14
0111	-4.375 V	7	1111	-9.375 V	15

Remember that the amplifier is an inverting amplifier, which is the reason for the negative voltages on the output. Some DACs allow the precision voltage to vary and are called *multiplying DACs* because the output is a result of the reference voltage times the voltage from the binary input.

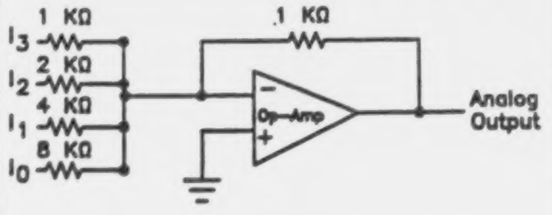
ADC CIRCUITRY

The ADC (analog digital convertor) circuit will convert an analog voltage to a binary word. The binary word will represent the analog input. The ADC unit in figure 2 shows how one type of ADC unit works. We have included only the parts that you are familiar with. We did not intend to accurately describe an ADC circuit, in this drawing, since a designer would not use a ripple counter in an ADC circuit. We put a ripple counter in the circuit because you are familiar with it, and it will help you understand the circuit.

Notice that the analog voltage is received into the positive input of the comparator. If we assume that the output of the DAC, which is feeding into the inverting input to the comparator, is low, then the comparator output will be high. The input analog voltage will be higher than the low from the DAC. A high on the positive input and a low on the negative input to the comparator will give a high on the output.

Notice the start input to the NAND gate. We can momentarily put a high on this start input, which will clear the ripple counter and put its 4-bit output to 0. This high on the start input goes low, which is inverted by the bubble on the input to the AND gate. This will give another 1 to the AND gate input.

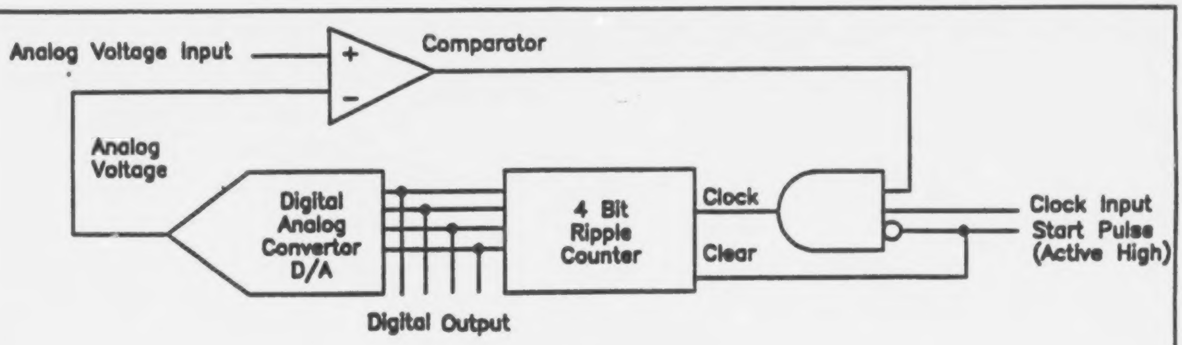
Notice the clock pulse input to the AND gate. The two highs on the AND gate will now allow the AND gate to pass the clock pulses. The clock pulses will pass on through the AND gate and start the ripple counter counting.



1 KΩ
I_3
2 KΩ
I_2
4 KΩ
I_1
8 KΩ
I_0
.1 KΩ
Op-Amp
Analog Output

Digital to Analog Conversion Circuit

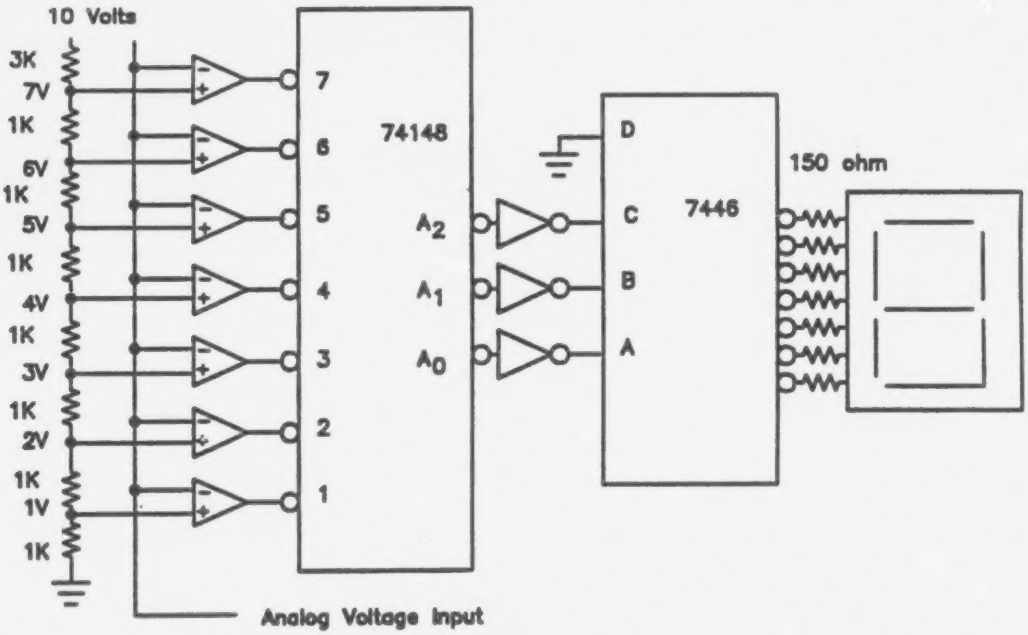
Figure 1



Analog Voltage Input
Comparator
Analog Voltage
Digital Analog Convertor D/A
4 Bit Ripple Counter
Clock
Clear
Clock Input
Start Pulse (Active High)
Digital Output

Analog to Digital Convertor

Figure 2



10 Volts
3K
7V
1K
6V
1K
5V
1K
4V
1K
3V
1K
2V
1K
1V
1K
7
6
5
4
3
2
1
74148
A_2
A_1
A_0
D
C
B
A
7446
150 ohm
Analog Voltage Input

Flash Analog to Digital circuit with 7 segment display

Figure 3

262

The voltage on the DAC output will be a function of the count or binary word from the ripple counter. As the count increases, the voltage will increase until the voltage out from the DAC equals the voltage on the positive input of the comparator.

When the voltage from the DAC passes the analog voltage on the positive input, the comparator will switch low, putting a low on the input to the AND gate. This will stop the clock pulses from getting to the ripple counter. The ripple counter will stop counting at that point and can be read from the digital output shown in figure 2.

The whole cycle can be repeated with another high on the start pulse. This will clear the ripple counter again. The cleared ripple counter will lower the voltage to the comparator, which will put a 1 on the AND gate. The 1 on the AND gate will allow the clock to start the ripple counter counting again.

This type of ADC takes a certain amount of time to count up until it reaches the analog input voltage. This circuit is not normally used where high speed is important. A much faster ADC convertor, called the *flash ADC convertor*, is shown in figure 3. The circuit in figure 3 includes additional circuitry to show a simple voltmeter. This type of ADC convertor will need considerable circuitry to get much resolution. We have drawn only a 3-bit device to show how the circuitry works.

The amount of circuitry needed for higher resolution becomes clear when we look at the number of comparators needed for a greater bit size. A 4-bit unit needs 15 comparators, and a 10-bit unit needs 1,023 comparators. The number of comparators needed is equal to 2^N-1 where N is the number of bits in the binary word.

Our example has a step size of 1 V. With 0 V on the analog input, all of the comparators will be feeding a high to the active low inputs of the 74148, which is a priority encoder. This will result in highs out the three outputs from the 74148 and a 0 on the seven-segment display.

Now let's change the analog input voltage to 3.5 V. The 3.5 V on the input will result in the inverting input on the bottom three comparators going higher than the positive input. This will cause these three comparators to go low on their outputs. The result will be the binary word for 3 on the output of the 74148. The binary word for 3 will feed into the 7446 and give a decimal 3 on the seven-segment display. Remember that the priority encoder will ignore all of the lower inputs and give an output based on the highest input that is active. This type of circuitry is fast because it does not count. The voltage on the input will show up as a binary word on the output after some propagation delay.

The PM-0820 is an ADC that uses two 4-bit flash units and a DAC. The manufacturer calls this chip a *half flash*. The combination of circuitry from the two types of ADCs has resulted in less circuitry and a very fast unit. An ADC circuit using the technology described in figure 2 will take approximately 15 µs to convert an analog voltage to a binary word. The manufacturer who builds this ADC unit also builds the half flash unit. The half flash unit can convert an analog voltage to a binary word in 1.5 µs, or ten times faster.

EXERCISE: Read each question carefully, and take your time. Use your notebook paper or scrap paper to solve the problems.

1. What is the highest frequency sine wave that you could transfer to digital numbers, if you used the half flash unit with the 1.5 μs and sampled each wave 10 times?
   - A. 9.4 MHz
   - B. 2.3 MHz
   - C. 6.7 MHz
   - D. 15.8 MHz
   - E. None of the above

2. If you were going to build an eight-input DAC using the op-amp with the inverting voltage feedback amplifier and an R_F of 1 kΩ, what resistor values would you need in the input?
   - A. 1 kΩ, 2 kΩ, 3 kΩ, 4 kΩ, 5 kΩ, 6 kΩ, 7 kΩ, 8 kΩ
   - B. 1 kΩ, 4 kΩ, 16 kΩ, 64 kΩ, 256 kΩ, 1.024 MΩ, 4.096 MΩ
   - C. 1 kΩ, 2 kΩ, 4 kΩ, 6 kΩ, 8 kΩ, 10 kΩ, 12 kΩ, 14 kΩ
   - D. 1 kΩ, 2 kΩ, 4 kΩ, 8 kΩ, 16 kΩ, 32 kΩ, 64 kΩ, 128 kΩ
   - E. None of the above

3. Give the resolution of a DAC with six inputs as a percentage of the total voltage.
   - A. 6.8%
   - B. 3.4%
   - C. 1.6%
   - D. 0.7%
   - E. None of the above

4. How many steps does the DAC in question 3 have?
   - A. 32
   - B. 64
   - C. 58
   - D. 72
   - E. None of the above

5. What is the number of comparators that would be needed for a 9-bit flash A/D?
   - A. 255
   - B. 511
   - C. 1,023
   - D. 2,047
   - E. None of the above

E-8

Data Transmission

UNIT OBJECTIVE: Upon completion of this instructional unit, the student will be able to demonstrate a knowledge of registers and adders and of circuits that convert analog to digital and transmit data.

SPECIFIC OBJECTIVES: Upon completion of this assignment, the student(s) will be able to demonstrate a knowledge of:

- the parity system
- fiber optics

TERMS

Parity: A system used to detect errors in transmitted digital data.
Fiber optics: Using glass fibers to transmit light which is modulated to carry data.
Baud rate: The number of bits per second that are transmitted.

ODD OR EVEN PARITY

When data is transmitted, noise and other factors will occasionally change some of the data, causing an error. Detecting these errors before the computer tries to process the data is very important. ***High levels of mathematics are used to find ways to locate and avoid errors. Your background in mathematics will help you understand some of the concepts presented in this assignment.***

Different methods of error detection have been developed. Noise and other problems will sometimes add or subtract a pulse or bit when data is transmitted. Detecting the addition or loss of a bit from noise and other factors is the problem. The *parity system* is one of the answers to the problem of finding errors in transmitted data. It can be used by itself as a simple system or as part of a more sophisticated system.

Before discussing parity, it may be helpful to discuss the ASCII code. The term *ASCII* is an abbreviation for the American Standard Code for Information Interchange. This is the code that is usually used to send data when transferring data from the keyboard of a computer to the computer, or talking between computers.

The basic word size in most computers is either 8 bits, 16 bits, 32 bits, or 64 bits. The ASCII word is 7 bits long, and this length was chosen to leave room for an extra bit, which can be the parity bit.

Parity may be either *odd* or *even*. If data is being sent using odd parity, then every word that is sent will have an odd number of 1s in it. It is common to send 8-bit words, and using ASCII will give you the extra bit for the parity bit. If you need to send odd parity, then the extra bit or the parity bit will be chosen so that the total count of 1s in the 8-bit word will be odd.

For example, the letter Q has the ASCII number 1010001. Notice that this word has three 1s in it, which makes it odd to begin with. Since the parity bit is usually put in the MSB position, this would make the 8-bit word that would be sent, 01010001.

If even parity were required, then the parity bit would be a 1. The receiving end uses circuitry to check each word for the number of 1s. If it counts either an odd number or an even number of 1s depending on the parity, no errors will be flagged.

Should a noise pulse cause an extra 1, the parity would be lost, and the equipment would register an error. If two 1s were added by noise, the error would not be caught. Having two errors in one word is not as likely as having just one error, but, with so much data being transmitted, it is possible.

To improve on the parity system, another technique is used to add an additional word that becomes part of the data word that is sent. This extra word is called the *check sum*. A 7-bit ASCII word with the parity bit is 8 bits. An additional 3-bit word with a parity bit also added to it can be sent along with the ASCII word. This additional word will simply be a count of the total number of 1s in the 7-bit ASCII word. If we use the letter Q as our example again, the 7-bit word with odd parity will have three 1s in it. The check sum 3-bit word would be the number 3 for the three 1s in the word or 011. Now we add a parity bit to this 3-bit word. The parity bit will be a 0 since the addition of the check sum still gives an odd number of 1s. The extra 4-bit word that is now added is 0011. The total word that is now transmitted is 10111010001. This is a total of 11 bits to transmit a 7-bit ASCII word. The possibility of an error not being caught has decreased.

There are situations where even this is not enough. For instance, the banking industry moves a very large amount of information between banks and terminals. Just losing one bit in the wrong place can be costly. To increase the reliability further, another step in error detection is to have the receiving end transmit the data back to the transmitting end and then compare received data against the original, bit for bit. Banks use additional checks beyond this to guarantee the integrity of the data they send back and forth.

RS-232C STANDARD

Most of the movement of data within a computer is done in parallel. When it is necessary to send data between computers, or from a computer to a printer, and the distance is relatively long, it is easier to send it in series. Parallel requires one wire for each bit of the data word. For a 32-bit computer, this is 32 wires. If the data is to be sent over the telephone wires, only one wire is available.

The UART, or universal asynchronous receiver transmitter, is the circuitry in a chip that is designed to convert the parallel data from the computer to data that can be sent in series.

The RS-232C standard is the specification for one method of transmitting data in series. Specifications and standards are necessary so that different pieces of equipment can be made to

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"talk" to each other. The RS-232C standard specifies a 25-pin connector on the computer or piece of equipment that will use this system. Each of the pins on the connector has a specified purpose.

The signals that will be sent over this system can be separated into four categories—the data signals, the control signals, the timing signals, and the ground returns of the system. Since this system was developed before computers, it does not use 0 and 5 V. The voltage levels for control signals are from -3 to -25 V for an on or high condition, and +3 to +25 V for an off condition.

The specification states that the maximum rate at which the signal may be sent is 10 Kbaud. One baud is 1 bit per second, so the number of bauds is equal to the number of bits per second (a *Kbaud* is 1,000 bauds).

Similar standards have been developed for transmitting data in parallel. Parallel data transfer is often used for short distances when speed is important.

TRANSMITTING DATA

Some methods of transmitting data are more error-prone than others. The cost of the system and the amount of data it can handle are also factors when an organization considers how it is going to transmit its data.

Usually, the data that is sent from a personal computer to a printer can be sent over ordinary wires with few problems. When the length of the run starts to increase, better wire is usually added to the system, and then interference and security problems can increase the cost of the cable running between computers and their peripherals.

Much of the data that is presently sent between computers or over longer distances is sent using coaxial cable. Coaxial cable has a copper conductor in the middle with insulation. Next, a second conductor in the form of a mesh is put around this insulation. Finally, a coating of insulation is placed around the whole cable.

There are inductive and capacitive effects between the center and outer conducting parts of coaxial cable that give it a particular impedance. The coax used for two-way radios has a 50 Ω impedance, and the coax used for television is 75 Ω. Should you confuse them, such as in an antenna installation, you will see a substantial loss in signal strength.

Coax cable has been around for some time, and the electronics industry has established standards for its manufacture. You can connect a plug from one manufacturer with a plug from another when using most coax cable. Coax cable itself is standardized and can be purchased from a variety of manufacturers with the knowledge that it will have the right impedance and the size will fit the standard plugs.

The fiber optics industry does not have any standards like this. Fiber optics does have some very big advantages over coax cable, but it is so new in the industry that no one manufacturer has been able to make its product or standards into an industry standard.

If you are part of a team installing a fiber optic system, you will need to obtain all of the materials from one source. Also, the cutting and preparing of the cable varies between manufacturers. Figure 1 shows some of the problems that can happen when connecting fiber optic cables. Notice the problem labeled *axial displacement*. Here the ends of the two glass fibers are not aligned. The problem of axial displacement is normally solved by the connector. Placing the

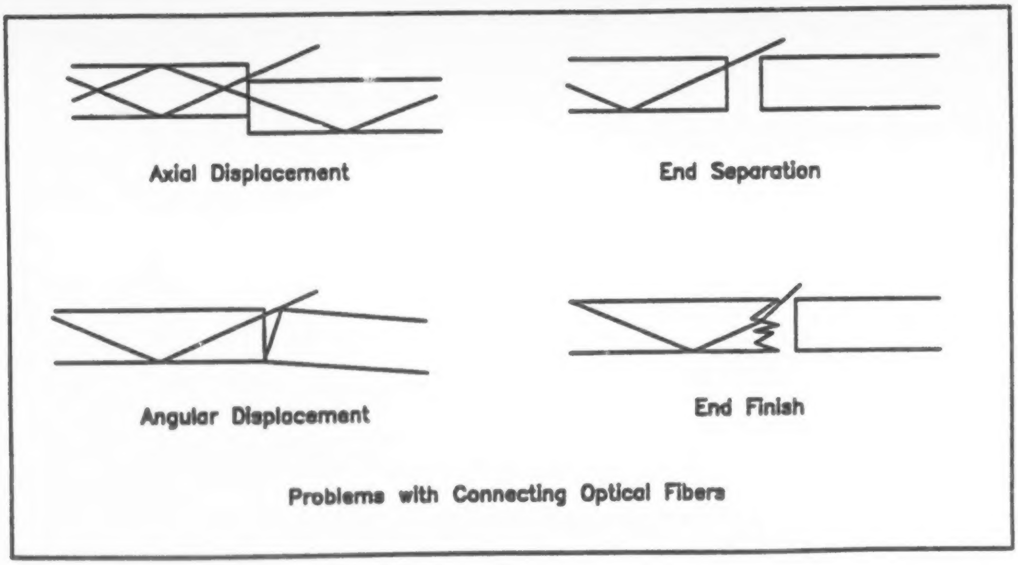
Axial Displacement
End Separation
Angular Displacement
End Finish
Problems with Connecting Optical Fibers

Figure 1

fiber optic conductors in a groove and butting them up against each other before locking them in place will eliminate this problem.

The *end separation* problem can be solved by using a glue with light properties similar to the glass fiber or using a torch to fuse the glass fibers together. Fusing them or glueing them tends to make a permanent connection, which may not always be desirable. Care in placing the fibers in the connector and in connecting the connectors is usually the solution to this problem.

The *angular displacement* problem should be solved with the use of good connectors that will not allow the fibers to be at an angle. The *end finish* can be a difficult problem. Care must be taken in cutting the glass fibers. The ends are polished by using a flat surface.

Test equipment has been developed that will check for losses in a fiber optic cable run. Large fiber optic systems will have more than one glass fiber in a cable. The telephone company has been installing large fiber optic systems to handle the heavy traffic between major cities. A system installed in California in 1983 can handle 240,000 digital channels with 64 Kbaud per channel.

LASER LIGHT

Ordinary light is composed of waves that are out of phase with each other. White light will have waves of different frequencies. Each color has its own frequency.

Laser light is unique in that it is both in phase and all the same frequency. Laser light is generated by stimulated emission. Another term is "pumping the laser" in which the material that will generate the laser is stimulated.

Different materials can be used to make a laser—solids such as ruby, gases such as helium and neon, and semiconductors such as gallium arsenide. The laser is made by putting mirrors at each end of the laser material. One mirror will reflect only a percentage of the light, and the other mirror will reflect all of the light.

When the material is excited by a strong light, the electrons in orbit in the material are moved out of their orbits. As they return to their orbits, they release light that is in phase and of one frequency—that is, laser light. The mirrors cause the light to bounce back and forth to increase the effect. The laser is released through the mirror which reflects only a portion of the light.

FUTURE

Fiber optics and lasers are very important for the long term in industry. A lot of research is going on to build more equipment using light beams. Researchers are trying to build switches that will use lasers to switch lasers. Logic gates could be built from switches like this. A complete computer using only light instead of electrons would be capable of much higher speeds.

EXERCISE: Read each question carefully, and take your time. Use your notebook paper or scrap paper to solve the problems.

1. What should the impedance of the coax be for a CB antenna?
   A. 100 Ω

B. 75 Ω
C. 50 Ω
D. As low as possible
E. None of the above

2. How long is an ASCII word in bits?
   A. 32 bits
   B. 16 bits
   C. 8 bits
   D. 7 bits
   E. None of the above

3. Which of the following words is not correct? Each word is using *even* parity and *is a binary coded decimal* for a total of a 5-bit word.
   A. 10100
   B. 11000
   C. 11001
   D. 00110
   E. None of the above

4. The parity system would catch the error if the right two bits were changed. What two bits would have to be changed?
   A. Parity bit and one other
   B. Two that are next to each other
   C. The LSB and the bit next to it
   D. Two 1s or two 0s
   E. None of the above

5. What is the difference between laser light and ordinary light?
   A. Laser light is stronger.
   B. Laser light cannot be reflected like ordinary light.
   C. Laser light is one frequency and in phase, which ordinary light is not.
   D. Ordinary light does not generate heat, and laser light will.
   E. None of the above

6. What is the RS-232C system?
   A. A system for detecting errors in transmitted data
   B. A system of transmitting data in parallel from a computer to a printer
   C. A set of standards for serial transmission of data
   D. A chip for converting parallel data to serial data
   E. None of the above

Unit
F
Computer Circuits

F-1: Memory Devices
F-2: Microprocessor Theory
F-3: Computer Language

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F-1

Memory Devices

UNIT OBJECTIVE: Upon completion of this instructional unit, the student will be able to demonstrate a knowledge of the concepts of the memory section of a computer, the microprocessor structure, and simple programming.

SPECIFIC OBJECTIVES: Upon completion of this assignment, the student(s) will be able to demonstrate a knowledge of:

- how a memory system is organized and addressed
- how data moves in and out of a memory system

TERMS

RAM: Random Access Memory is memory that can be written into and read from. This type of memory is also volatile.

Volatile memory: This memory is lost when the power is removed.

ROM: Read Only Memory is memory that cannot be changed or written into.

RWM: Read Write Memory; the term RAM is often used instead of this term.

Byte: A byte is 8 bits. A nibble is 4 bits. A bit is the basic and smallest unit that a computer handles.

Read operation: Reading the data in storage or taking the data from storage.

Write operation: Putting data into storage or writing it into storage.

Static memory devices: This type of memory will remain as long as power is applied and does not need to have the information rewritten into it periodically.

Dynamic memory: This type of memory must have the data periodically refreshed or it will be lost.

COMPUTER SYSTEM

Previously, you studied the flip-flop and its use in registers as a memory device. The computer uses this type of memory along with some of its variations. The flip-flop registers are in ICs that we usually call RAM or RWM. A RAM or RWM is a volatile read write memory. If a flip-flop register loses its power, all of the data will be lost. The term *volatile* is used to describe this situation. The registers are formed into memory units that can hold a large number of bits.

The dynamic memory is another type of popular memory device. The dynamic memory system will store data by charging capacitors. Since the data will leak off the capacitors, this type of memory must be refreshed periodically. The advantage of this type of memory is the very large amount of data that can be stored in one chip at a reasonably low cost.

The magnetic type of storage such as the floppy disk, hard disk, and magnetic tape, is used for mass storage outside of the computer. This type of memory device will hold large amounts of storage at a cheap cost but is slow in reading data or writing data.

MEMORY TERMINOLOGY

Many terms have been developed to describe the different parts of a memory system. For example, a memory unit with eight registers and 16 flip-flops in each register would be described as having a capacity of 8 words and each word would be 16 bits long. Note that each flip-flop holds one bit, and the size of the register determines the size of the word. We would write this as 8 X 16. This would be a total of 128 bits for this memory unit. ***Your background in algebra will help you understand this system of describing memory.***

The number of words in a memory unit will normally equal 2 to some power because this is a more efficient use of the number of address lines that it takes to address these words. As a result, it is unusual to have just 1,000 words. You will normally find 1,024, which equals 2^{10}, as the number of words or a multiple of this amount. This is why, in describing the number of words in memory, *1K* is equal to 1,024 and not 1,000.

If we have a memory unit with 8K X 16 capacity, it has 8,192 words (8 X 1,024) with 16 bits per word. The *address* of a word is the location of the word in the chip. With the larger memory units, an address will locate a position by activating one line (called a *row*) that crosses that point horizontally and one line (called a *column*) that crosses that point vertically.

A memory unit that can be both written into and read from and is volatile, such as registers made up of flip-flops, is often called RAM, although RWM would be more correct.

The ROM (read only memory) is programmed or read into only once at the factory. It is a nonvolatile type of memory that will often hold the basic instructions for a computer. Nonvolatile means that it will hold its memory when the power is removed from the chip.

The PROM is a programmable ROM. One type of PROM has fusible links which are burned by passing high currents through them in the programming process. This type of PROM can be programmed only once, but it can be programmed in the field instead of at the factory. The EPROM is a programmable read only memory that can be removed from the circuit, erased with ultraviolet light, and reprogrammed.

The EEPROM can be programmed in the circuit with higher than normal voltages. The EEPROM requires voltages above 12 V to reprogram the chip. When this chip is used in portable equipment, there is often only 12 V available. Special power supplies, consisting of an oscillator with a step-up transformer or voltage tripler using capacitors and diodes, are used to get the higher voltages necessary. These EEPROMs are often used in two-way radios to store the data for generating the frequencies for the radios. To change the frequency, a technician would press a certain combination of buttons on the front of the radio, and then go through a process of feeding in the frequency information and storing it for each channel. Another model of radio allows the radio to be connected to a computer station, and the frequency information is downloaded into the radio.

The PROM, EPROM, and EEPROM are all used to store program data for portable equipment that must retain its memory when power is removed. Two-way radios are one common application of this technology.

MEMORY ICs

In figure 1, we have taken the 74670 memory chip, which is a 4 X 4 device, and redrawn it. Figure 1 does not faithfully represent the whole device. This memory chip has four registers of flip-flops with four flip-flops in each register. It is a very small memory device that has been made to be very fast. Figure 1 leaves out some of the circuitry. We have simplified the address inputs and removed the circuitry for the data out. You will find it easier to understand how the address inputs work with the simpler logic that we have added.

The circuitry on the right side for the data out included some AND and NOR gates that are used to combine the four outputs into one, which is controlled by the READ address inputs. This resulted in only four data outputs from the chip. The data in, the data out, and each of the two address inputs all have their own bus systems. The data-in bus would be four lines that connect to this chip and to possibly other chips and input output devices as well. Without all this extra circuitry, you can concentrate on the important part of the circuit to understand how a memory chip is able to store data.

In figure 1, a word can be placed on the data-in bus, and it will appear at the chip on the four lines, which puts it at each of the registers. The four data-in lines are labeled I_0, I_1, I_2, and I_3. We left off the circuitry that will enable the chip. This enable circuitry will put a 0 on all of the AND gates feeding the clock inputs of the chips.

Until this enable line is cleared, none of the registers will accept the data. Now looking at the address inputs, if we put a 0 on both the A and B inputs and examine the logic, we will see that the A column or Word 0 will have 1s on both inputs to their AND gates. Notice that the word 0 is the column on the left side and is labeled at the top. This will trigger the flip-flop, and the data will be stored on the Q outputs of these flip-flops.

For this particular chip, data can be written in at the same time that data is being read out of the chip. This is not done with the larger chips, which will have only one address input for read and write. They will also usually have only one set of pins for both input and output which will be connected to the data bus. This will result in one address bus and one data bus.

A small computer usually has one additional bus, called the control bus. The control bus might operate the chip enable lines, although they are often controlled by the address bus. A computer with an 8-bit word size could use these chips. We would arrange the chips in pairs so the data inputs pick up four of the data lines for each chip. This would be an eight-line data bus. With an 8-bit word, the address inputs could be in parallel, resulting in each address picking up half of the word from each chip.

To increase the number of words requires a little more work with the address inputs. We can double the number of words by using the enable line. This can be done by putting the existing address lines in parallel and putting an inverter between the enable lines. This arrangement would then require a 3-bit address bus.

DYNAMIC MEMORY DEVICES

Most of the smaller computers used in businesses and for home use have dynamic memory chips, or DRAMs, for their working memory. This type of memory stores the data on small capacitors in the chip. Like all capacitors, the capacitors used for storage will leak the data off. The data has to be rewritten or refreshed periodically. The data will remain for about 2 ms before it is lost. Additional circuitry, which may be in the chip or as additional chips, is used to refresh the memory.

DRAM memory has a word size of only 1 bit. If these chips were addressed in the usual manner, the address bus would become very large. To reduce the number of address lines for a large array of DRAM chips, address multiplexing is used.

The address to be sent to the memory units is first sent to a chip which divides it in half and only sends half of it at a time. The circuitry will send the row address first. This row information is held and the row is activated. Then the second half of the address is sent to activate the column. The point where the row and column meet is the location for that 1-bit word.

EXERCISE: Read each question carefully, and take your time. Use your notebook paper or scrap paper to solve the problems.

1. How many bits are in a memory unit with the capacity of 3K X 8?
   A. 24,000
   B. 2,400
   C. 24,576
   D. 8,192
   E. None of the above

2. How many address locations are in the memory unit in question 1?
   A. 3,000
   B. 3,072
   C. 8,000
   D. 8,192
   E. None of the above

3. What is the word size for the memory unit in question 1?
   A. 3 bits
   B. 24 bits
   C. 1,024 bits
   D. 8 bits
   E. None of the above

4. What would you call a memory system that used D flip-flops in its registers?
   A. ROM
   B. EPROM
   C. RAM
   D. DRAM
   E. None of the above

5. What do you call a memory system that stores its data on a capacitor?
   A. ROM
   B. EPROM
   C. RAM
   D. DRAM
   E. None of the above

6. What word size does dynamic memory have?
   A. 8 bit
   B. 4 bit
   C. 2 bit
   D. 1 bit
   E. None of the above

7. How is the EPROM reprogrammed?
   A. A higher than normal voltage is used.
   B. Ultraviolet light is used to erase it, and then it is reprogrammed.
   C. A computer is used to download the data.
   D. The chip is heated to erase it and then cooled for reprogramming.
   E. None of the above

8. Why does the computer refresh dynamic memory?
   A. To remove any errors
   B. The registers become tired.
   C. To recharge the internal capacitors
   D. To clear any blank areas for more data
   E. None of the above

9. What type of device is the 74670?
   A. Dynamic memory chip
   B. Address control chip
   C. Static memory device
   D. Interface chip
   E. None of the above

10. How many bits are in a byte, and how many bits in a nibble?
   A. 6 and 4
   B. 8 and 4
   C. 6 and 2
   D. 8 and 16
   E. None of the above

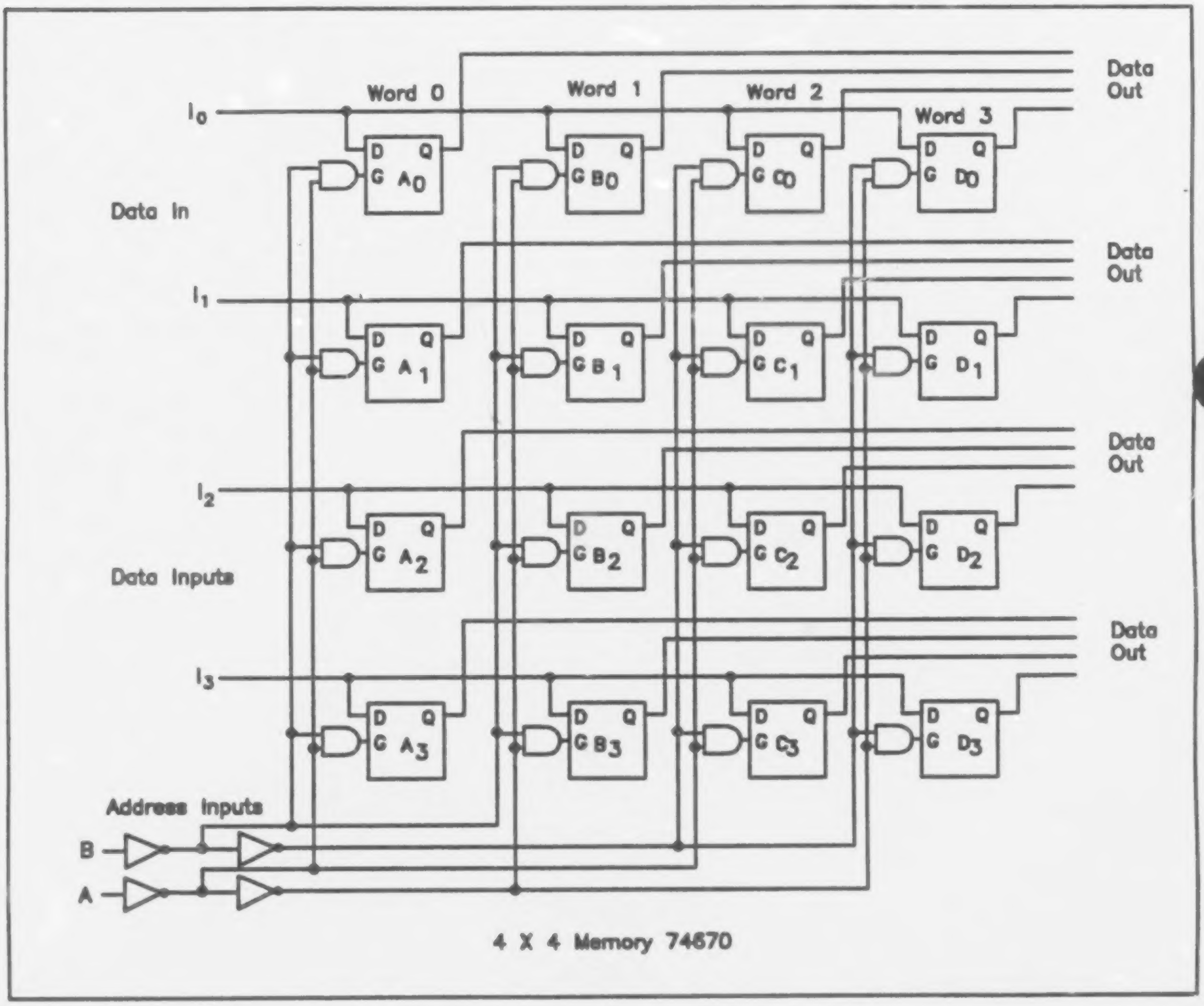

Word 0
Word 1
Word 2
Word 3
Data Out
Data Out
Data Out
Data Out
I_0
I_1
I_2
I_3
Data In
Data Inputs
D Q G A_0
D Q G B_0
D Q G C_0
D Q G D_0
D Q G A_1
D Q G B_1
D Q G C_1
D Q G D_1
D Q G A_2
D Q G B_2
D Q G C_2
D Q G D_2
D Q G A_3
D Q G B_3
D Q G C_3
D Q G D_3
Address Inputs
B
A
4 X 4 Memory 74670

Figure 1

F-2

Microprocessor Theory

UNIT OBJECTIVE: Upon completion of this instructional unit, the student will be able to demonstrate a knowledge of the concepts of the memory section of a computer, the microprocessor structure, and simple programming.

SPECIFIC OBJECTIVES: Upon completion of this assignment, the student(s) will be able to demonstrate a knowledge of:

- how a microprocessor is organized
- how the microprocessor can address and move data

TERMS

Accumulator: The accumulator in a 6809-based system is composed of two 8-bit registers that can be combined into one 16-bit register.

Condition code register: The CC or condition code register holds the flags that show the status of the microprocessor (μP).

Control bus: This bus provides the signals that control the various functions of the microprocessor and the external devices.

Data bus: This bus carries data to and from the μP to the memory and I/O devices.

Address bus: This bus carries the address information to the memory and I/O devices.

THE COMPUTER

The modern computer has a microprocessor, which contains the control and processing circuitry, a complete bus system, memory, and the input/output devices. We will use *μP* for microprocessor, which is an industry standard abbreviation. ***Your background in algebra and trigonometry classes have helped you think in a logical manner. This logical thinking will help you as you study the microprocessor (μP).***

The Motorola μP, called the 6809, is the μP that we will be using as our example. This μP is similar to others of the same size. The 6809 has an 8-bit data bus and a 16-bit address bus.

The bus system used by the 6809 consists of three buses—the address bus, the data bus, and the control bus. The *address bus* is used to send the address information from the μP to both the memory and the input/output buffers. These buffers are connected to the input/output ports or plugs. The term *input/output* is abbreviated as *I/O*. The address bus will take the address information from the computer and send it to its destination. The address information only travels one way on the address bus.

The *data bus* will take information from the µP and deliver it to the memory section or the I/O devices. The data bus will also receive data from these devices. The data bus is bidirectional, which means that information travels in both directions on this bus.

The *control bus* is a collection of control lines. Each of the control lines will operate in only one direction. Some of the control lines operate going into the µP, and some going out. However, the control bus as a whole is considered to be bidirectional. The interrupt lines, which are part of the control bus, are used to stop the µP when requested by an external piece of equipment such as a printer. The computer can easily transmit data to a printer much faster than most printers can print. Most printers have a buffer memory which stores the data from the computer. When the buffer memory is full, the interrupt line is used to tell the computer to stop sending data.

Notice the shaded bus lines in figure 1. The usual method for drawing bus with a large number of lines is to show a broad line with arrows. If we tried to show all the individual lines, we would only generate confusion. The arrows in a bus line drawing show the direction in which information flows.

Notice that the control bus shows both directions to the µP and the I/O ports. The control signals go only to the memory devices. The memory devices do not send control signals back to the µP. Signals are sent and received from the I/O ports.

A way to remember the control bus is to consider it as a collection of all the other signal lines minus the address and data bus lines.

THE MICROPROCESSOR

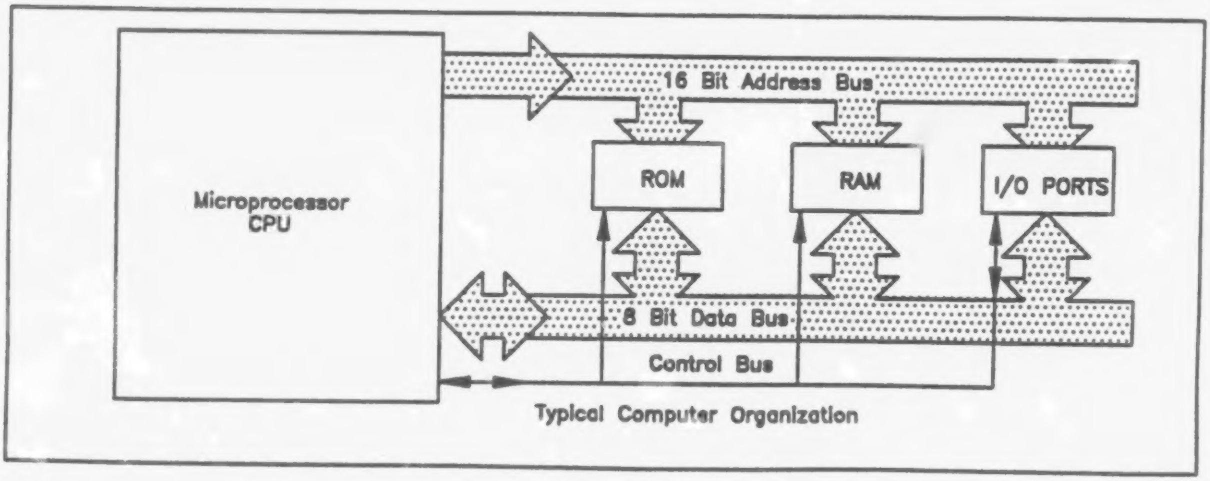
The µP is a chip full of circuitry which is connected to its support circuitry through the bus lines. These bus lines connect all the internal registers and operating sections of the µP. They also connect the µP to the external memory and I/O devices.

Notice in figure 2, on the right side of the drawing, the PC or *program counter*. The PC is shown in the box with the bus lines coming and going from the top and bottom. This register is used to sequentially increase the address each time it puts a new address on the address bus. The instructions or program can cause the PC to jump to a different address.

The next block to the left is the *accumulator*, which has both the A and B registers in it. The 6809 µP allows the programmer to write instructions that will use the A and B registers as one register. The program counter and the other registers that feed the address bus are all 16-bit registers. The A register is an 8-bit register, and the B register is also an 8-bit register. Together they make the full 16-bit register. When they are used together, they are called the D register. You will learn later how these two registers are used when programming the computer.

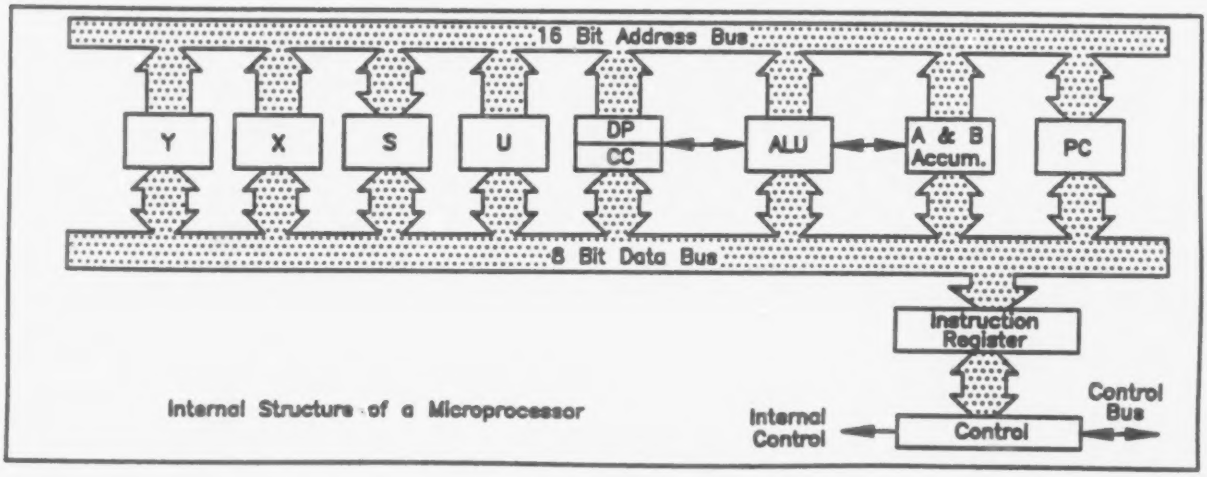
The next block to the left is the *arithmetic logic unit*. The ALU resembles the adder that you have studied. The A and B registers that fed the adder are the same A and B registers we have here. The ALU both sends and receives data from the CC or condition code register.

The *condition code register* is an 8-bit register that is used to determine the condition or status of the µP. Each of the 8 bits in the CC register is called a *flag*. For example, the Z flag, which is


Microprocessor CPU
16 Bit Address Bus
ROM
RAM
I/O PORTS
8 Bit Data Bus
Control Bus

Typical Computer Organization

Figure 1


16 Bit Address Bus
Y
X
S
U
DP
CC
ALU
A & B Accum.
PC
8 Bit Data Bus
Instruction Register
Internal Control
Control
Control Bus

Internal Structure of a Microprocessor

Figure 2

the third bit from the LSB in the register, will go high when the sum from the ALU is zero. The N flag will go high when the ALU has a negative number for its sum. The F flag can be set high to stop a control line from interrupting the μP.

The DP or *direct page register* above the CC register provides half the address during operation of the computer. This speeds up the processing of data. The X and Y registers are called *index registers* and are used to index an address location. This means the index registers can be used to put an address on the address bus that is calculated instead of simply stated. The advantage of this can be appreciated when you begin to program the computer.

The U and S registers are called *stack pointer registers*. The U register is the user stack pointer register and can be used by the programmer. The S or hardware stack pointer register is automatically used by the computer to hold data temporarily during an operation. Both the S and U registers are available to a programmer, although the S register has limitations because of its use by the computer.

On the right side of figure 2 is the *instruction register*. The IR or instruction register will receive data from the data bus and decode it. These are the instructions to the computer for each step that it takes.

MICROPROCESSOR REQUIREMENTS

The 6809 μP requires 5 V on pin 7, which is labeled VCC. The ground connection is pin 1, labeled VSS. This chip has a total of 40 pins. Four of the pins are for the clock signals. The 6809 requires two overlapping clock signals. They should overlap at the 180°, point or about halfway. This will result in two leading edges and two trailing edges. These four timing points are used to start and stop various functions in the μP.

The two signals are located on pins 34 and 35 and are labeled E and Q. The E clock is used for timing signals on the bus system. The leading edge of the E clock will tell the μP that data is stable, and the μP can send a control signal to memory or the I/O devices to begin write operations.

The trailing edge of E is used to stop the movement of data which moves only when the Q clock is high. The leading edge of the Q clock will tell the μP that the address information is valid to the memory or I/O devices. The two clock signals must be set up so the Q clock leads the E clock by half a pulse.

Besides the clock signals, all outputs from the μP to the data bus must be tristate-controlled. The address bus does not need to be tristate since it is a one-way bus with the μP as the only output.

OTHER MICROPROCESSORS

The 6800 family of μP was first introduced by Motorola in 1974 with the 6800 chip. Then came the 6801, a revised version of the 6800. The 6801 is faster than the 6800 and has some additional codes that the programmer can use. The next revision was the 6802, which added an internal clock to the μP. Another member of the family is the 6805, which was designed to be a complete computer in one chip. The 6809, the last of this family, added additional registers to the basic µP and additional methods of programming the computer.

The next major development in µP by Motorola was the 68000 series. The 6800 series is an 8-bit µP, and the 68000 is a 16-bit µP. The 68000 has 32-bit registers instead of the 16-bit ones in the 6800 series. It has a 24-bit address bus, which allows it to address 16 megabytes of memory.

The total amount of memory that a µP can access is equal to 2^N. The N is the size of its address bus. The 6800 with the 16-bit address bus can access 2^{16} or 64K of memory. Remember that 1K, when dealing with computer memory, is equal to 1,024.

Another very popular µP is the Z 80 made by Zilog. The Z 80 is actually the Z8400. The Z8400 series is similar to Motorola's 6800 series, and the Z8000 series is similar to Motorola's 68000 series. Intel also makes a very popular µP used in many small computers.

EXERCISE: Read each question carefully, and take your time. Use your notebook paper or scrap paper to solve the problems.

1. How many lines are there in the address bus and the data bus in the 6809 µP system?
    A. 64 bits and 32 bits
    B. 32 bits and 16 bits
    C. 16 bits and 8 bits
    D. 8 bits and 4 bits
    E. None of the above

2. Which bus allows information to go only one way?
    A. Data bus
    B. Control bus
    C. Address bus
    D. School bus
    E. None of the above

3. Which bus system has the line that tells the memory chip to store the data that is on the data bus?
    A. Data bus
    B. Control bus
    C. Address bus
    D. School bus
    E. None of the above

4. How many flags does the condition code register have?
    A. 16
    B. 12

C. 8
D. 4
E. None of the above

5. How many pins does the 6809 µP have?
A. 120
B. 80
C. 40
D. 32
E. None of the above

6. What is the name of the register that decodes data from the data bus to determine what step to take next?
A. PC register
B. DP register
C. CC register
D. Instruction register
E. None of the above

7. What is the maximum memory that a µP with an 8-bit address bus can access?
A. 512 bits
B. 256 bits
C. 128 bits
D. 1024 bits
E. None of the above

8. What is the register called that will increase the address each time it puts an address on the address bus?
A. Direct page register
B. Condition code register
C. Accumulator register
D. Program counter register
E. None of the above

9. What is the size of the address bus for the new 68000 series of µP?
A. 36 bits
B. 24 bits
C. 18 bits
D. 16 bits
E. None of the above

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Computer Language

UNIT OBJECTIVE: Upon completion of this instructional unit, the student will be able to demonstrate a knowledge of the concepts of the memory section of a computer, the microprocessor structure, and simple programming.

SPECIFIC OBJECTIVES: Upon completion of this assignment, the student(s) will be able to demonstrate a knowledge of:

- how a program will control a computer
- how a program can be written

TERMS

Assembler: A program that will convert the mnemonics to binary code for the computer to use.

Instruction words: Contain the operation the computer is going to perform and the address of the data to be operated on.

Machine language: The instructions to the computer in binary code which the machine or computer understands.

Mnemonics: A code of 3 or 4 letters that represents a binary number code. These are the instructions to the computer.

Op-code: The operation code, which is the instruction to the computer for the operation to be performed.

Operand address: The address where the data is stored. The op-code and the operand address are the two parts of the instruction word.

COMPUTER LANGUAGE

A computer is a combination of integrated circuits, which we call the *hardware*, and the instructions to the computer, which we call the *software*. The concept of having a machine follow instructions in sequence (a *program*) resulted in the computers we know today.

The computer can only understand and deal with binary code or 1s and 0s. It is difficult for people to work with numbers that are just 1s and 0s. For people to be able to write complex programs or instructions for computers, higher level programs have been developed.

Your studies in English and grammar will help you understand this new language used to communicate with the computer. Unlike people, the computer requires accuracy in its communications.

An assembly language program was developed for each type of microprocessor. These assembly language programs are different for each µP. This program translates a three or four letter word into the appropriate 1s and 0s for the computer.

Even the assembly language programs can be time-consuming and difficult. Languages at a higher level than assembly have been developed. Some of the higher level languages are BASIC, Fortran, Cobol, and Pascal.

To understand how a program controls the computer, we will start by examining the assembly language designed for the 6809 µP, since we have been using the 6809 µP as our example. All assembly language programs look similar. The primary difference between them is in the translation to machine code.

Before you can learn any language, whether foreign or computer, you need to learn some vocabulary. We will start with a brief vocabulary of the *op-codes* for the assembly language. The op-codes are the instructions to the computer. Each line of instruction will include an op-code and usually an address or a reference to an address.

ADDA: This instruction will add the contents of the memory location specified in the location address to the contents of accumulator or register A and store the result in register A. Note that the instruction looks like ADD A.

CLR: This will clear or put 0s in the address location specified. This one should be easy to remember. CLR is close to the word *clear*.

JMP: This instruction will cause the program counter to put the address on the address bus specified and proceed from that address. JMP looks like *jump*, and that is what the instruction causes the program counter to do.

LDA or LDB: This instruction will load the contents of register A or B into the memory location specified. Notice that LD looks like the word *load*.

STA or STB: This instruction will store the contents of register A or B in the location specified. The term ST looks like *store*.

SWI: This instruction will halt the µP or the program. Maybe you can remember this one by thinking of the interrupt line.

Now that we have a small vocabulary, we can talk to the computer. We can start by writing a short program using this vocabulary. Let's assume that the number 5 is in address location $0850 and the number 4 is in address location $0925. We put the dollar sign in front of the address locations to indicate that the number is hexadecimal. This dollar sign notation is used only in programming and is recognized by the computer as hexadecimal.

0100	LDA	$0850	Load A with the data in location $0850.
0200	ADDA	$0925	Add the contents of register A or accumulator A to the contents of address location $0925 and put the results in accumulator A.

```
0300   STA    $0675            Store the contents of register A in address location
                               $0675.

0400   SWI

0500   DONE
```

When you write a program, it is always a good idea to document it. The documentation is a brief explanation of the programming instructions. This documentation will help you understand what the program is doing on each line. For more complex programs, programmers rarely get all of their instructions correct, and the documentation helps to debug or find the errors. The documentation is on the right side of the page. The documentation will have no affect on the program itself.

It is customary to write a program such as this using the assembly language program. In other words, we would write this program on the very computer where we will use it. When we are finished writing our program, we will have the assembly language program translate it into binary code and store it in the memory of the computer. This process is called "assembling the program into the computer."

The assembler or assembly language program will put our instructions into the RAM memory of the computer. Since we specified certain address locations such as $0850, $0925, and $0675, we have to be careful where the computer puts our program. It could write the program over these memory locations.

A better program will not have specific address locations in the program. Motorola calls such a program *position independence*. This means the program is independent of any address location and can be put anywhere. In our program, we were specifically picking up data from specified address locations, so a position independence program is harder to achieve.

Let's now assume that our program has been translated into machine code and stored, starting at location $1200. When we run the program, the computer is going to start at location $1200 and follow directions.

The first instruction that the computer sees is to load accumulator A with the contents of address location $0850. The column of numbers on the left side of the page is used to index our instructions. The op-code is the column with the term *LDA*, and the address location follows it in the next column.

The next instruction tells the computer to add the contents of accumulator A to the contents of address location $0925. We have a 5 in accumulator A at the present, and we are going to read address location $0925. The data that is in location $0925 is the number 4. The number 4 is put on the data bus and brought to the ALU. There the 5 and the 4 will be added, and the sum, which is 9, will go to accumulator A .

The next step is to store the contents of accumulator A in address location $0925. For the computer to execute this instruction, it first has the program counter place the next address location on the address bus after the completion of the last instruction. This address from the PC will be the address that holds the STA instruction. The binary code for the STA instruction will go to the instruction register where it is decoded. The decoded instructions are then sent to control.

Upon the next clock pulse, the program counter puts the next address on the address bus which is the address $0925. The control puts the read write line low, which means write. The contents of accumulator A are put on the data bus and are loaded into address location $0925.

Finally, the next instruction will stop the program. The last instruction that we wrote is used to tell the assembler to stop assembling the program. When the program is run, this last instruction is not used.

The assembly language program for the 6809 has a total of 44 different instructions. This set of instructions increases to close to 200 when the different address modes are considered.

The different addressing modes are the different ways to present the address location in the instructions. For example, the indexed mode uses the index registers to calculate the address location. In our example, we used extended addressing, which is not used in position independent programs. The instruction SWI, which stops the program, is in the inherent mode. This mode is for instructions with no effective address.

The assembly language program allows a programmer to manipulate the registers and data in the computer itself. A programmer is able to work where the action is. The problem with this type of program is that it will take a long time to write a complex program. Higher level languages are needed for bigger programs.

A higher level language will give you one command that will use many of the commands in the assembly language program. A good programmer might use the assembly language to write a small program that can be used in a larger higher level program. The higher level program can jump down to the assembly language program for a specific task and then jump back up.

EXERCISE: Read each question carefully, and take your time. Use your notebook paper or scrap paper to solve the problems.

1. What does the dollar sign in front of an address location mean?
   A. It designates an address location.
   B. It reminds the programmer that time is money.
   C. It tells the computer that this address is in hexadecimal.
   D. It tells the computer to find that address.
   E. None of the above

2. What is an *operand*?
   A. Operational part of the instruction
   B. Address location in an instruction word
   C. A type of address location
   D. A method of giving address locations
   E. None of the above

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3. What does *position independence* mean?
   A. Writing lines of instruction in any position in the program
   B. The position of the program counter is not important.
   C. This involves address locations that move around.
   D. A program which does not reference a specific address location
   E. None of the above

4. What does the op-code *ADDB* mean?
   A. Add A and B.
   B. Add the data in the specified address location to the data in the B register.
   C. Add the totals in the B register.
   D. Add the B and D registers.
   E. None of the above

5. What does the term *flag* mean to a programmer?
   A. A signal that there is a mistake in the program
   B. A flag indicates the program is running too fast.
   C. A flag shows the condition of the µP.
   D. Flags are used to decorate the program.
   E. None of the above

6. What does the op-code *LDA* mean?
   A. Load the A register contents into the D register.
   B. Leave the A and the D register empty.
   C. Load the A register with the contents of the specified address location.
   D. Remove the contents of the D register to the specified address location.
   E. None of the above

7. What is *Pascal?*
   A. This register is located next to the Y register in the 6809 µP.
   B. Pascal is part of the control bus.
   C. Pascal is a higher level language.
   D. Pascal is part of the I/O devices.
   E. None of the above

8. What is the index addressing mode?
   A. It is a method of sorting the address locations.
   B. The programmer will use this mode to find a location.
   C. This mode will put the address locations far enough away from the main program to avoid problems.
   D. It is an addressing mode that uses the index register to calculate the address location.
   E. None of the above

9. How does documentation affect the program?
   - A. It helps guide the program to the correct instructions.
   - B. It speeds up the running of the program.
   - C. It reduces the number of errors in a program.
   - D. The program will not run without it.
   - E. None of the above

COMPLIANCE STATEMENT

TITLE VI, CIVIL RIGHTS ACT OF 1964; THE MODIFIED COURT ORDER, CIVIL ACTION 5281, FEDERAL DISTRICT COURT, EASTERN DISTRICT OF TEXAS, TYLER DIVISION

Reviews of local education agencies pertaining to compliance with Title VI Civil Rights Act of 1964 and with specific requirements of the Modified Court Order, Civil Action No. 5281, Federal District Court, Eastern District of Texas, Tyler Division are conducted periodically by staff representatives of the Texas Education Agency. These reviews cover at least the following policies and practices:

(1) acceptance policies on student transfers from other school districts;

(2) operation of school bus routes or runs on a non-segregated basis;

(3) nondiscrimination in extracurricular activities and the use of school facilities;

(4) nondiscriminatory practices in the hiring, assigning, promoting, paying, demoting, reassigning, or dismissing of faculty and staff members who work with children;

(5) enrollment and assignment of students without discrimination on the basis of race, color, or national origin;

(6) nondiscriminatory practices relating to the use of a student's first language; and

(7) evidence of published procedures for hearing complaints and grievances.

In addition to conducting reviews, the Texas Education Agency staff representatives check complaints of discrimination made by a citizen or citizens residing in a school district where it is alleged discriminatory practices have occurred or are occurring.

Where a violation of Title VI of the Civil Rights Act is found, the findings are reported to the Office for Civil Rights, Department of Health, Education and Welfare.

If there is a direct violation of the Court Order in Civil Action No. 5281 that cannot be cleared through negotiation, the sanctions required by the Court Order are applied.

TITLE VII, CIVIL RIGHTS ACT OF 1964; EXECUTIVE ORDERS 11246 and 11375; TITLE IX 1973 EDUCATION AMENDMENTS; REHABILITATION ACT OF 1973 AS AMENDED; 1974 AMENDMENTS TO THE WAGE-HOUR LAW EXPANDING THE AGE DISCRIMINATION IN EMPLOYMENT ACT OF 1967; VIETNAM ERA VETERANS READJUSTMENT ASSISTANCE ACT OF 1972 AS AMENDED IN 1974.

It is the policy of the Texas Education Agency to comply fully with the nondiscrimination provisions of all federal and state laws and regulation by assuring that no person shall be excluded from consideration for recruitment, selection, appointment, training, promotion, retention, or any other personnel action, or be denied any benefits or participation in any programs of activities which it operates on the grounds of race, religion, color, national origin, sex, handicap, age, or veteran status (except where age, sex, or handicap constitute a bona fide occupational qualification necessary to proper and efficient administration). The Texas Education Agency makes positive efforts to employ and advance in employment all protected groups.